CR 151008

MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-4-8

ORBITER ENTRY TRAJECTORY CORRIDORS - 32,000 POUND PAYLOAD, 67.5% CENTER OF GRAVITY

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

9 JULY 1975

This Design Note is Submitted to NASA Under Task Order No. D0303, Task Assignment 1.4-4-A in Fulfillment of Contract NAS 9-13970.

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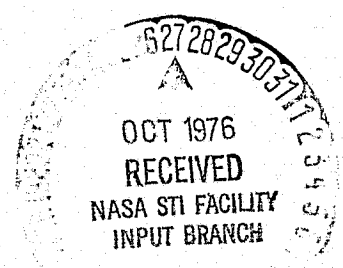


1.0 SUMMARY

This design note presents plots of Orbiter thermal and equilibrium glide boundaries in the drag/mass-relative velocity (D/M-V), dynamic pressure-relative velocity ($\bar{q}$-V), and altitude-relative velocity (h-V) planes for an Orbiter having a 32,000 pound payload and a 67.5% center of gravity (cg) location. These boundaries were defined for control points 1 through 4 of the Shuttle Orbiter for 40°-30° and 38°-28° ramped angle of attack entry profiles and 40°, 38°, 35°, 30°, 28°, and 25° constant angle of attack entry profiles each at 20°, 15°, and 10° constant body flap settings.

2.0 INTRODUCTION

Thermal and equilibrium glide boundaries are used to analyze and/or design Shuttle Orbiter entry trajectories. The boundaries presented in this note were used by the Flight Performance Branch (FPB) of the NASA for trajectory profile shaping of entry trajectories corresponding to a vehicle weight of 193,000 pounds (32,000 pound payload) and a 67.5% cg location. These conditions are consistent with a 28.5° inclination Eastern Test Range (ETR) mission and were used by the FPB to evaluate an ETR mission in support of Thermal Protection System (TPS) design.

3.0 DISCUSSION

Plots of thermal and equilibrium glide boundaries in the D/M-V (Figures 2-49), $\bar{q}$-V (Figures 50-97), and h-V (Figures 98-145) planes are presented for the 40°-30° and 38°-28° ramped angle of attack profiles and the 40°, 38°, 35°, 30°, 28°, and 25° constant angle of attack profiles each at 20°, 15°, and 10° constant body flap settings. The 40°-30° and 38°-28° ramped angle of attack profiles are presented in Figure 1.

The data presented in the note were generated using the Thermal Boundary Analysis Program (TBAP) (Reference 1) which uses simplified heating models in defining thermal boundaries. Revisions to TBAP for this study include a more sophisticated method in determining the normal shock viscosity coefficient (Reference 2), updates to the transition criteria on control point 2 by representing the normal shock Reynold's number as a function of angle of attack and body flap deflection angle (Reference 3), and updated transition criteria for control point 4 (Reference 4).

The equilibrium glide boundaries were generated using a digital program to solve the equilibrium glide equation:

$$D/M = \frac{g}{\frac{L}{D}\cos\phi}\left(1 - \frac{V_I^2}{V_{sat}^2}\right) \qquad (3\text{-}1)$$

D = drag force (lbs)

M = mass (slugs)

V_I = inertial velocity (ft/sec)

g = gravitational acceleration (ft/sec^2)

L/D = lift-to-drag ratio (-)

ϕ = roll angle

V_{sat} = sattelite velocity (ft/sec)

It should be noted, in equation (3-1), that data for the equilibrium glide boundaries in the D/M-V planes were calculated as a function of inertial velocity (V_I) but were plotted versus relative velocity (V) as though $V = V_I$. Therefore, for the data to be meaningful, a transformation from inertial to relative velocity must be applied. In the D/M-V plane this can be done by shifting the data by the difference in the inertial and relative velocities for the trajectory of interest. An approximate transformation is

$$V = V_I - \omega R \cos i \qquad (3\text{-}2)$$

where

ω = earth rotation rate (radians/sec)

R = earth radius (ft)

and i = orbit inclination (radians).

Equation (3-2) is least accurate for polar orbits, exhibiting a maximum error of about 45 ft/sec. On the D/M-V boundary figures

presented in this note a 45 ft/sec. error is negligible. Hence, equation (3-2) can be used to adjust the equilibrium glide boundaries to account for orbit inclination.

The equilibrium glide boundaries in the $\bar{q}$-V and h-V planes can be determined from the drag equation:

$$D/M = \frac{\rho V^2 C_D S}{2M} \tag{3-3}$$

where D/M is determined from equation 3-2 and

C_D = aerodynamic drag coefficient (-)

S = reference area (ft^2)

ρ = free stream density ($slug/ft^3$)

that is

$$\bar{q} = \frac{1}{2} \rho V^2 = \left(\frac{D}{M}\right) \frac{M}{C_D S} \tag{3-4}$$

and h = function of ρ

$$\text{where } \rho = \left(\frac{D}{M}\right) \frac{2M}{V^2 C_D S} \tag{3-5}$$

The solution of (3-4) and (3-5) requires an iteration on altitude since C_D is a function of altitude through the Mach number and since h is not easily represented as a direct function of ρ for the 1962 standard atmosphere.

The data for the equilibrium glide boundaries in the $\bar{q}$-V and h-V planes are accurate only for 90° orbit inclinations (i.e. orbits for which $V \simeq V_I$). Unlike the equilibrium glide boundaries in the D/M-V plane, a simple "shifting" of the boundaries in the $\bar{q}$-V and h-V planes is not possible. Determination of the boundaries in these planes requires independent generation of the data for each orbit inclination of interest. Note, however, that the analytic drag control entry guidance software operates in the D/M-V plane and the data presented in that plane can be adjusted for orbit inclination thus providing all the information required for profile shaping for any orbit inclination.

4.0 REFERENCES

1. Evans, M. E.: "Thermal Boundaries Analysis Program Document", MDTSCO, SSEOS Design Note No. 1.4-4-5, 30 April 1975.

2. Greenschlag, S. N.: "An Improvement in Normal Shock Viscosity Estimates", Rockwell International Internal Letter SAS-AA&T-75-102, 24 March 1975.

3. Haney, J. W.: "Revision to Control Point 2 of the Entry Flight Mode Optimization Program", Rockwell International Internal Letter SAS-AA&T-75-042, 14 February 1975.

4. Haney, J. W.: "Revision to Control Point 4 of the Entry Flight Mode Optimization Program", Rockwell International Internal Letter ASA-AA&T-74-072, 5 March 1975.

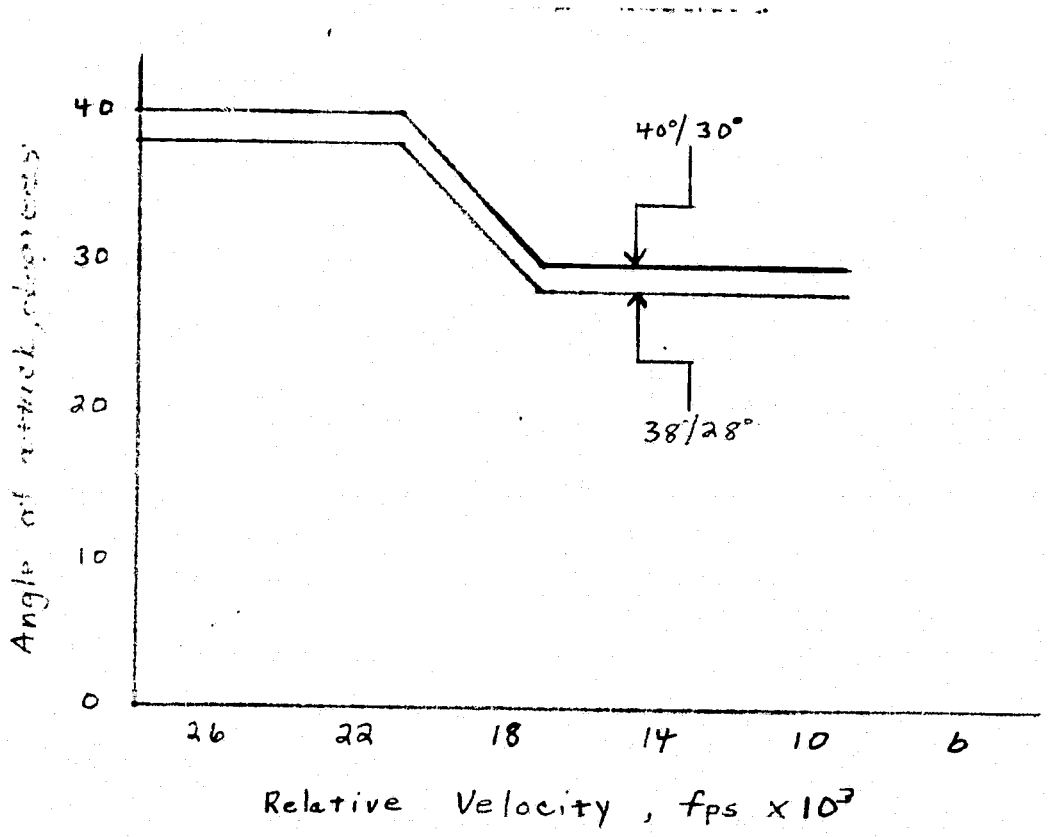
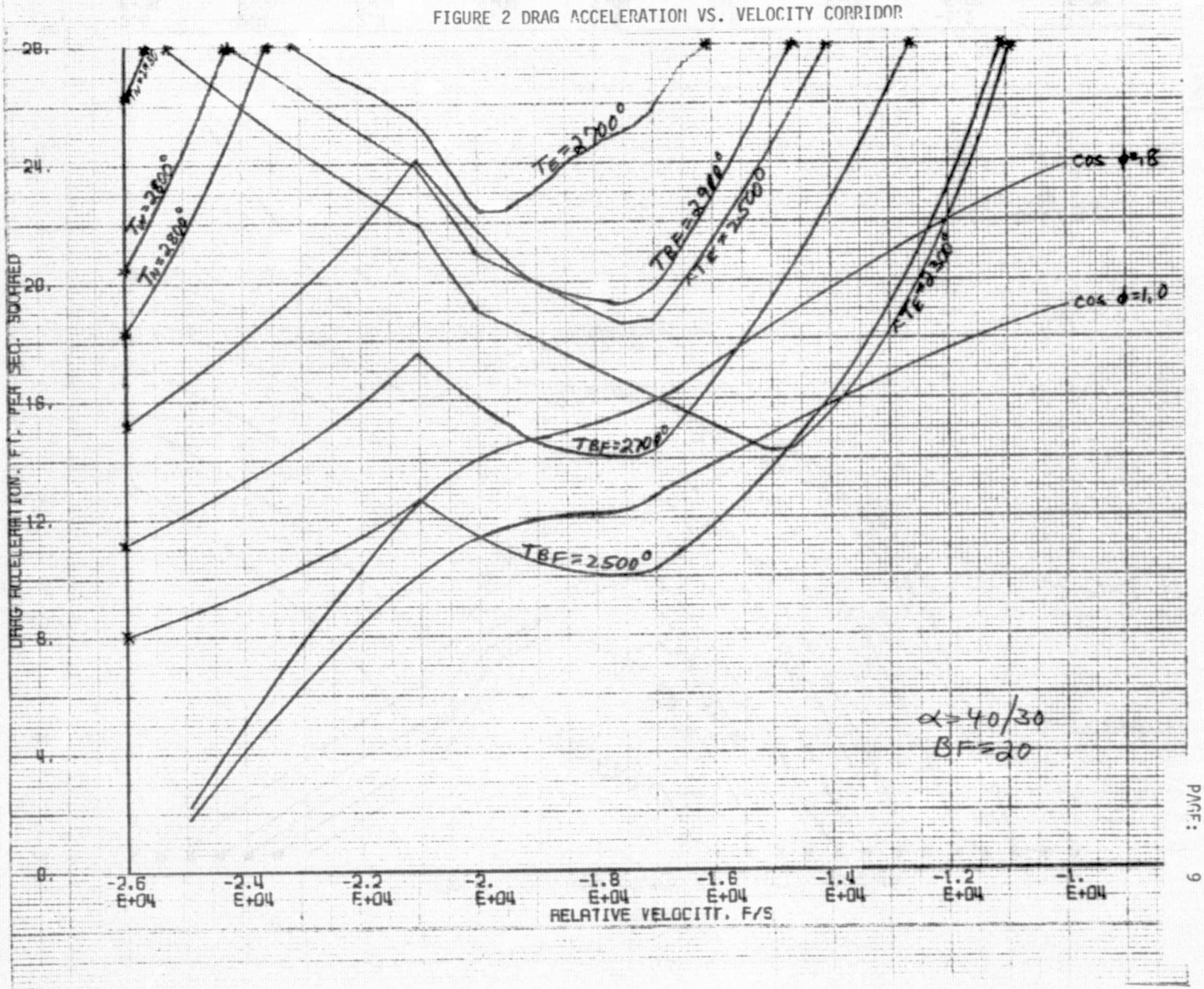


Figure 1

RAMPED ANGLE-OF-ATTACK PROFILES AS A FUNCTION OF RELATIVE VELOCITY

FIGURE 2 DRAG ACCELERATION VS. VELOCITY CORRIDOR



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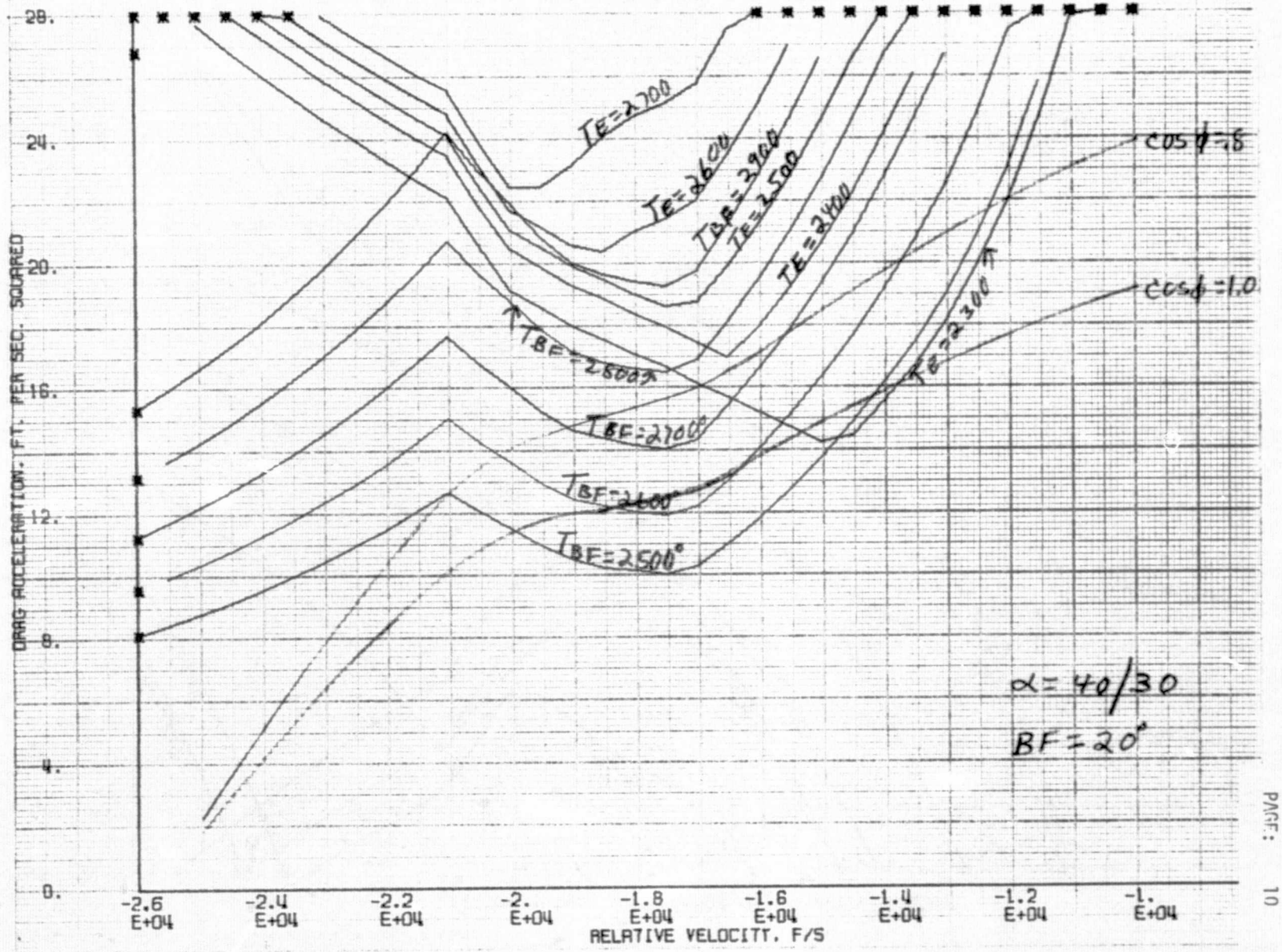

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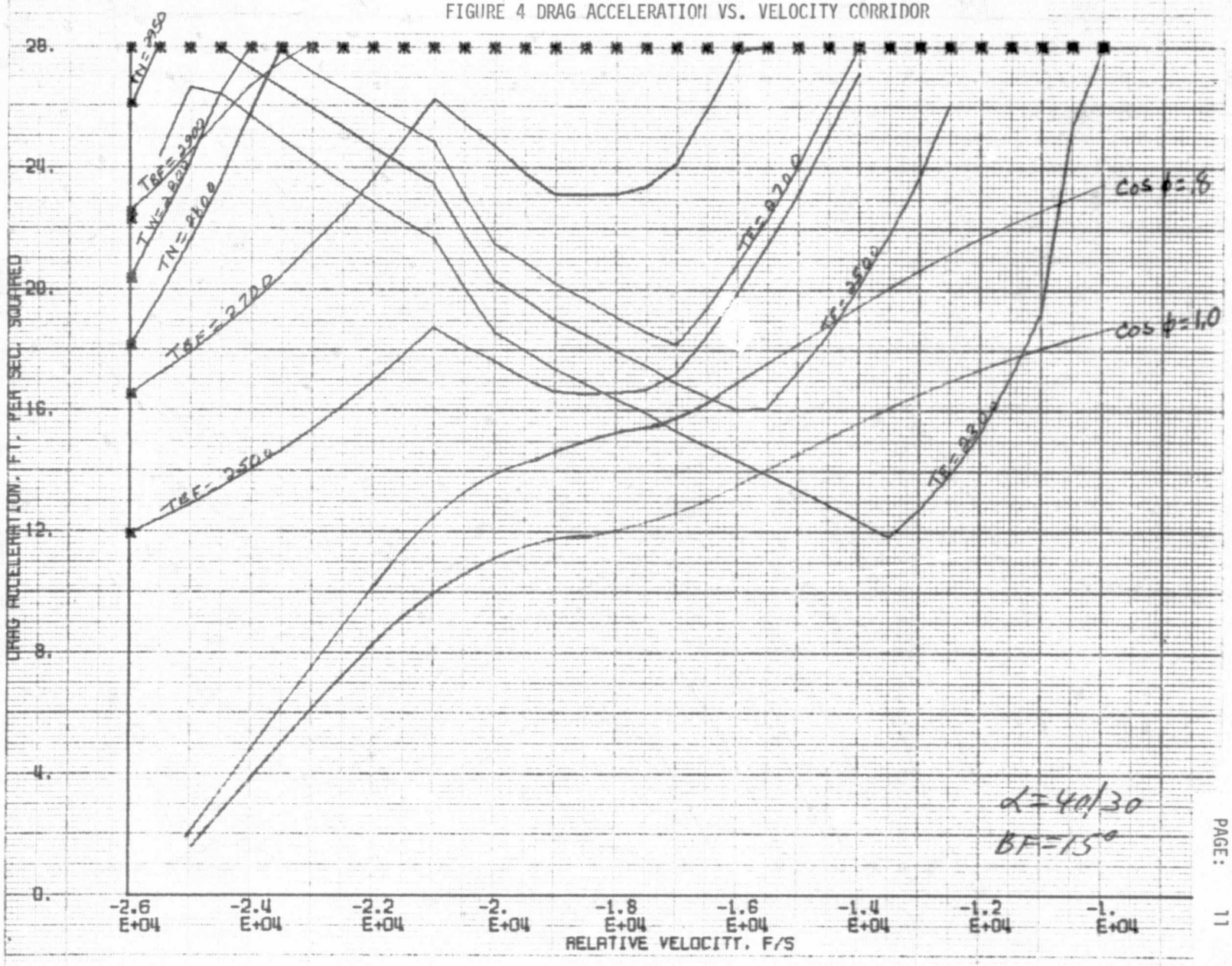

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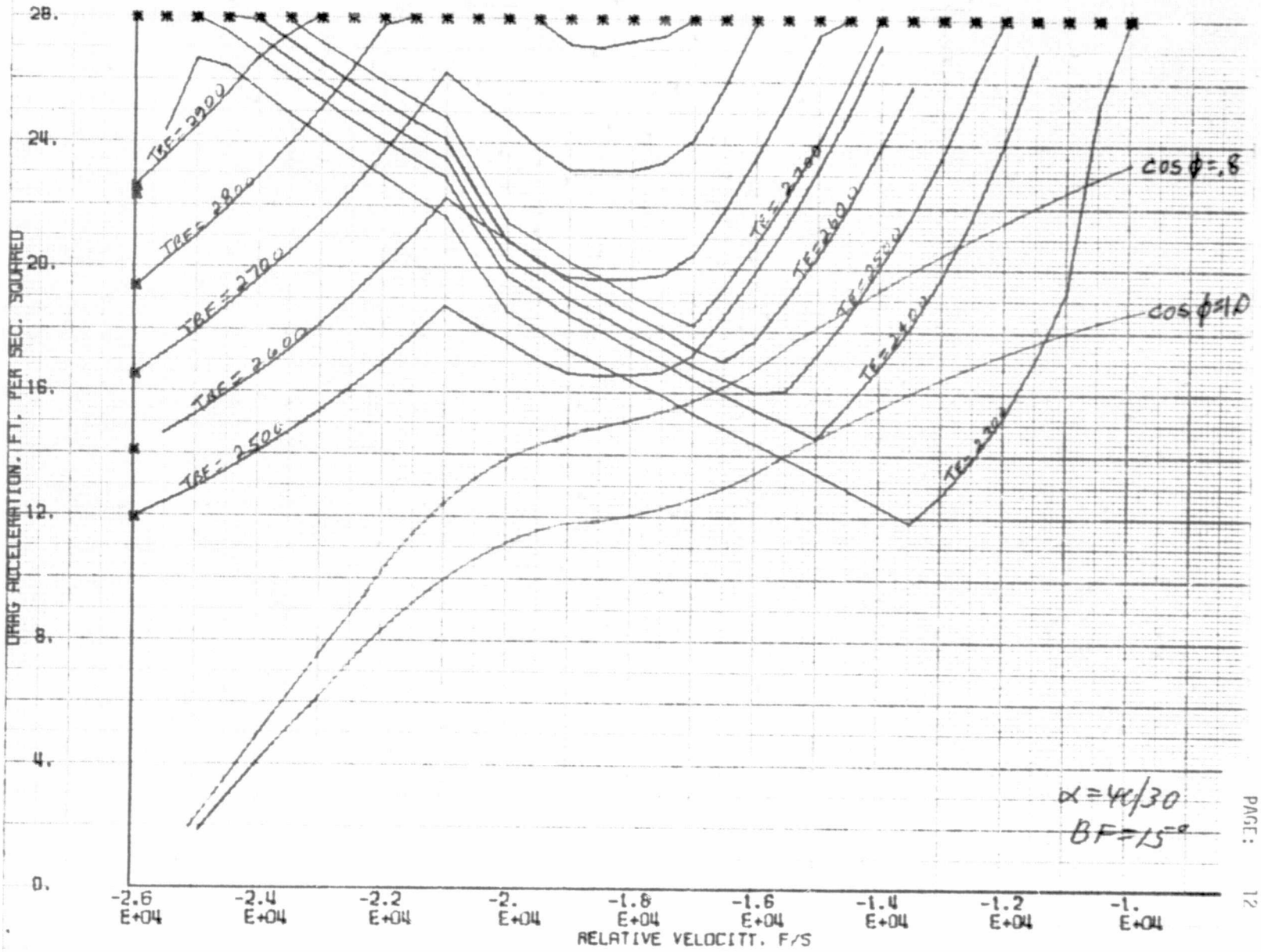

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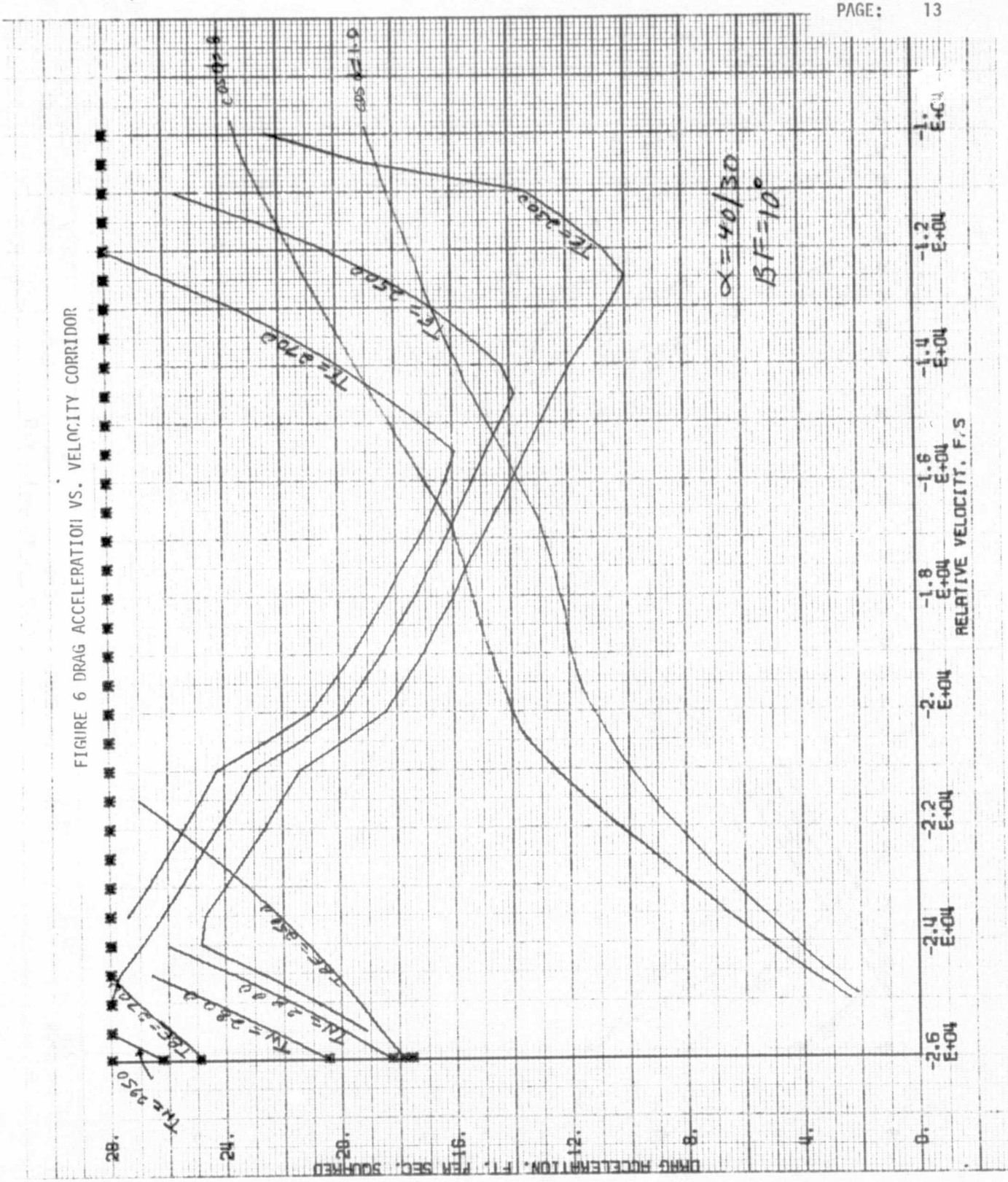
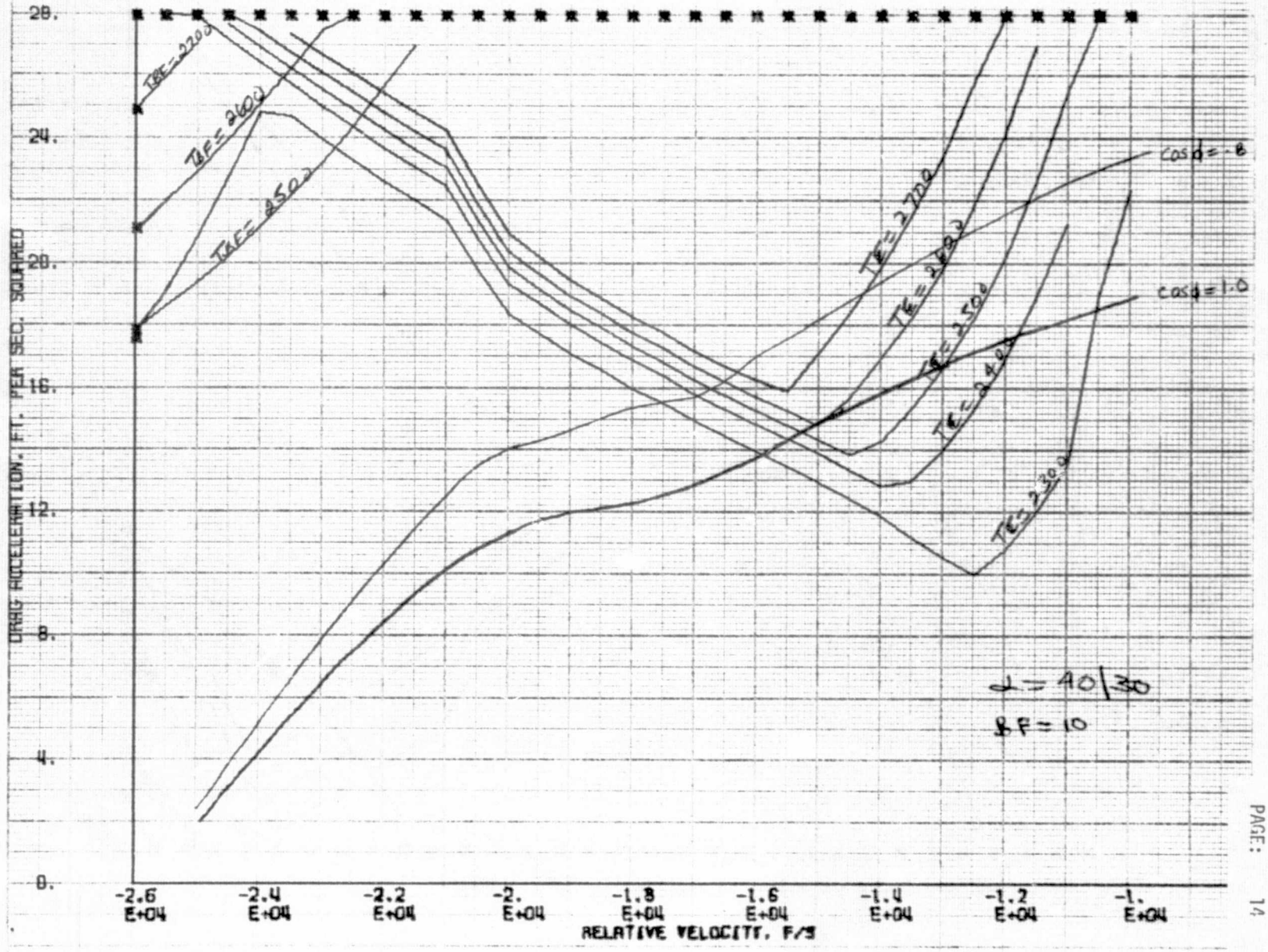


FIGURE 6 DRAG ACCELERATION VS. VELOCITY CORRIDOR

FIGURE 7 DRAG ACCELERATION VS. VELOCITY CORRIDOR



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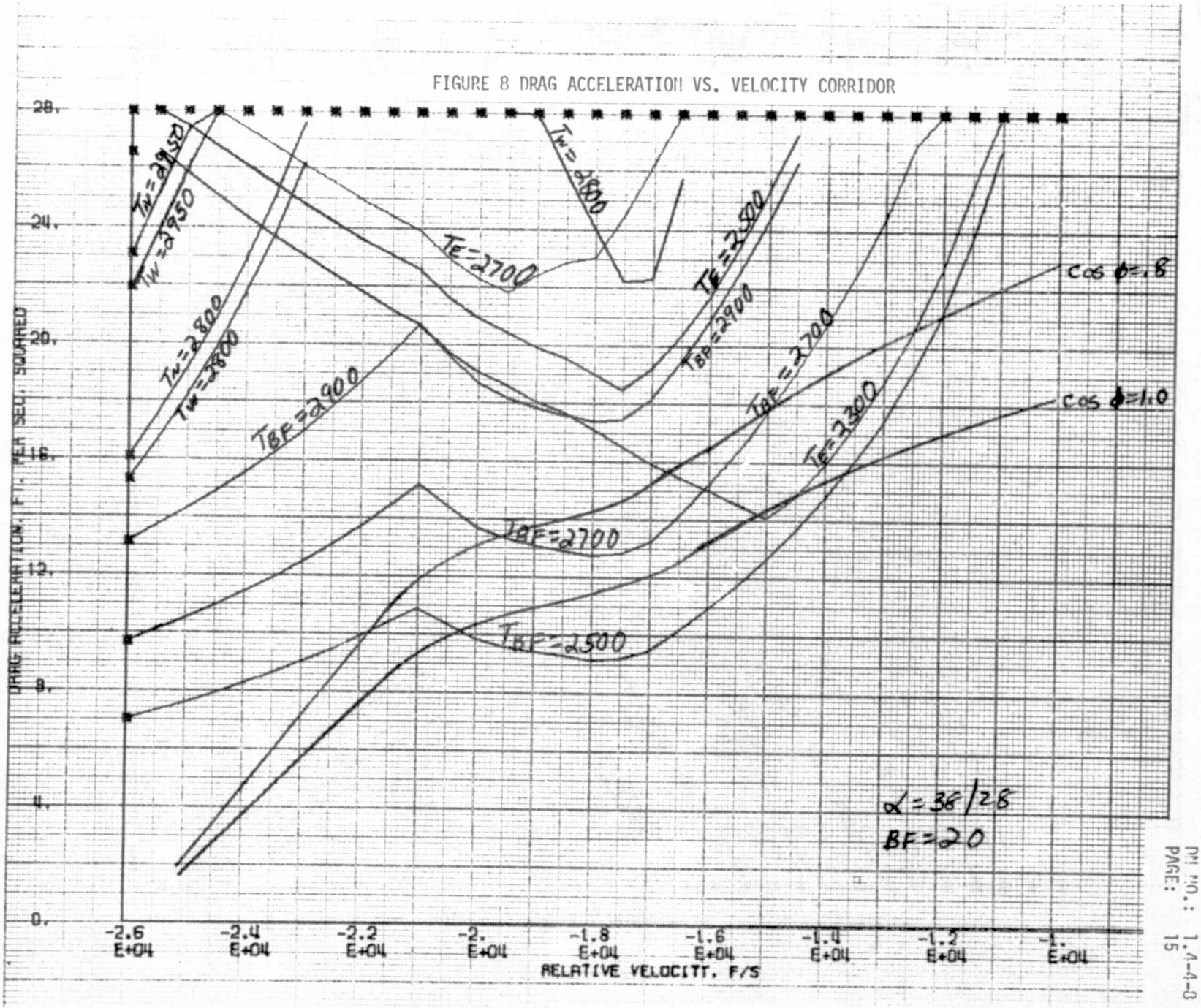

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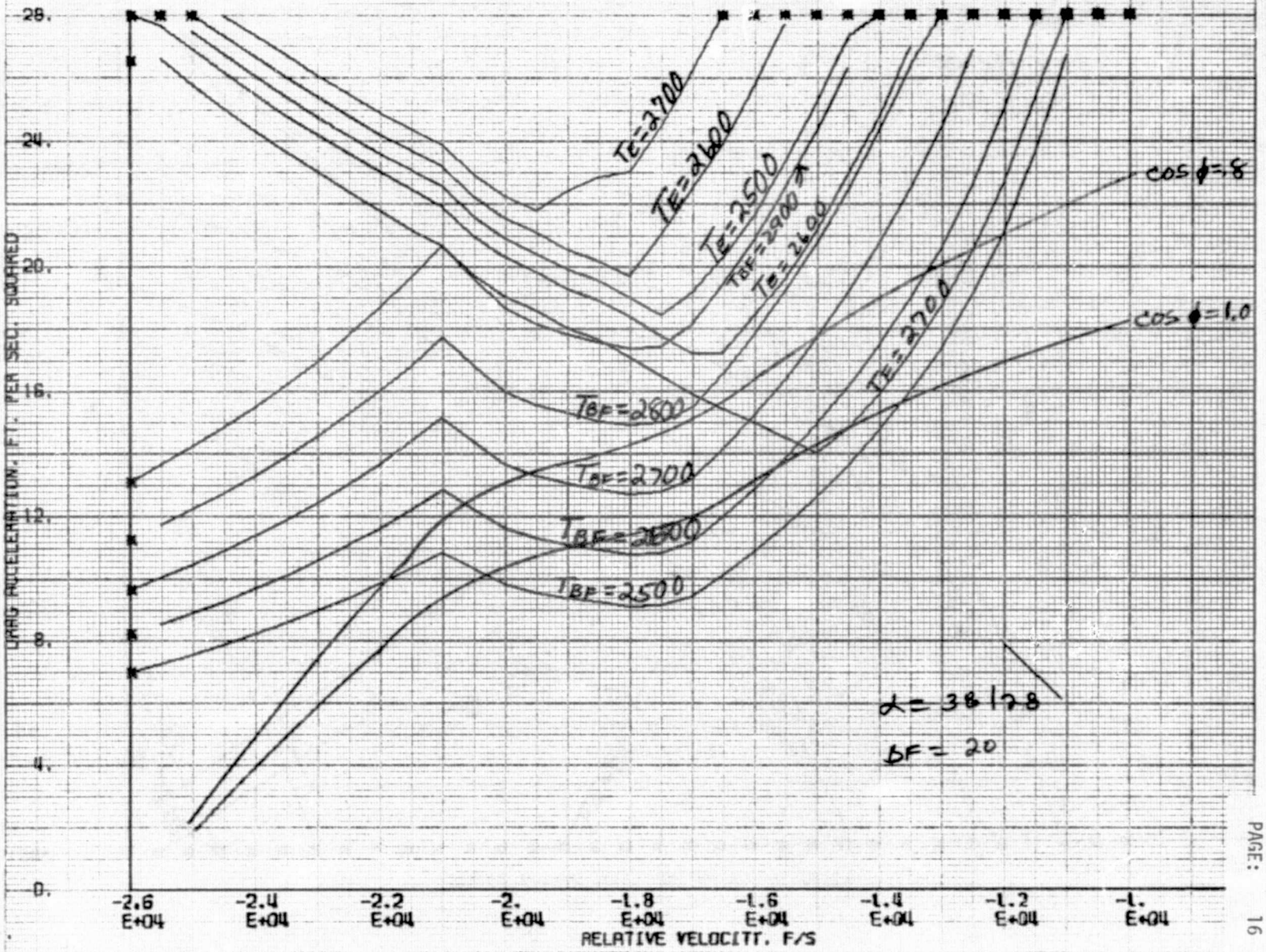

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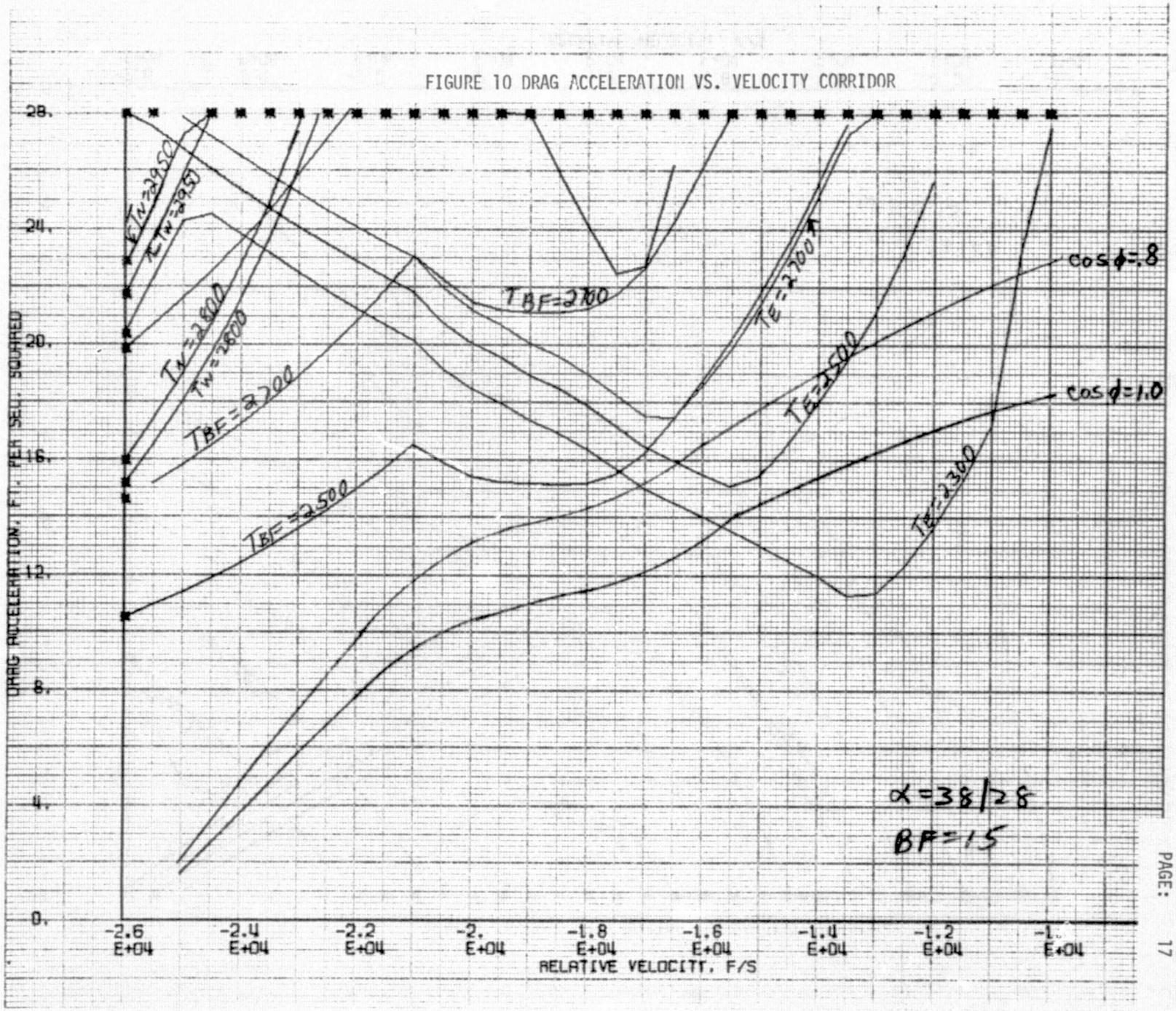

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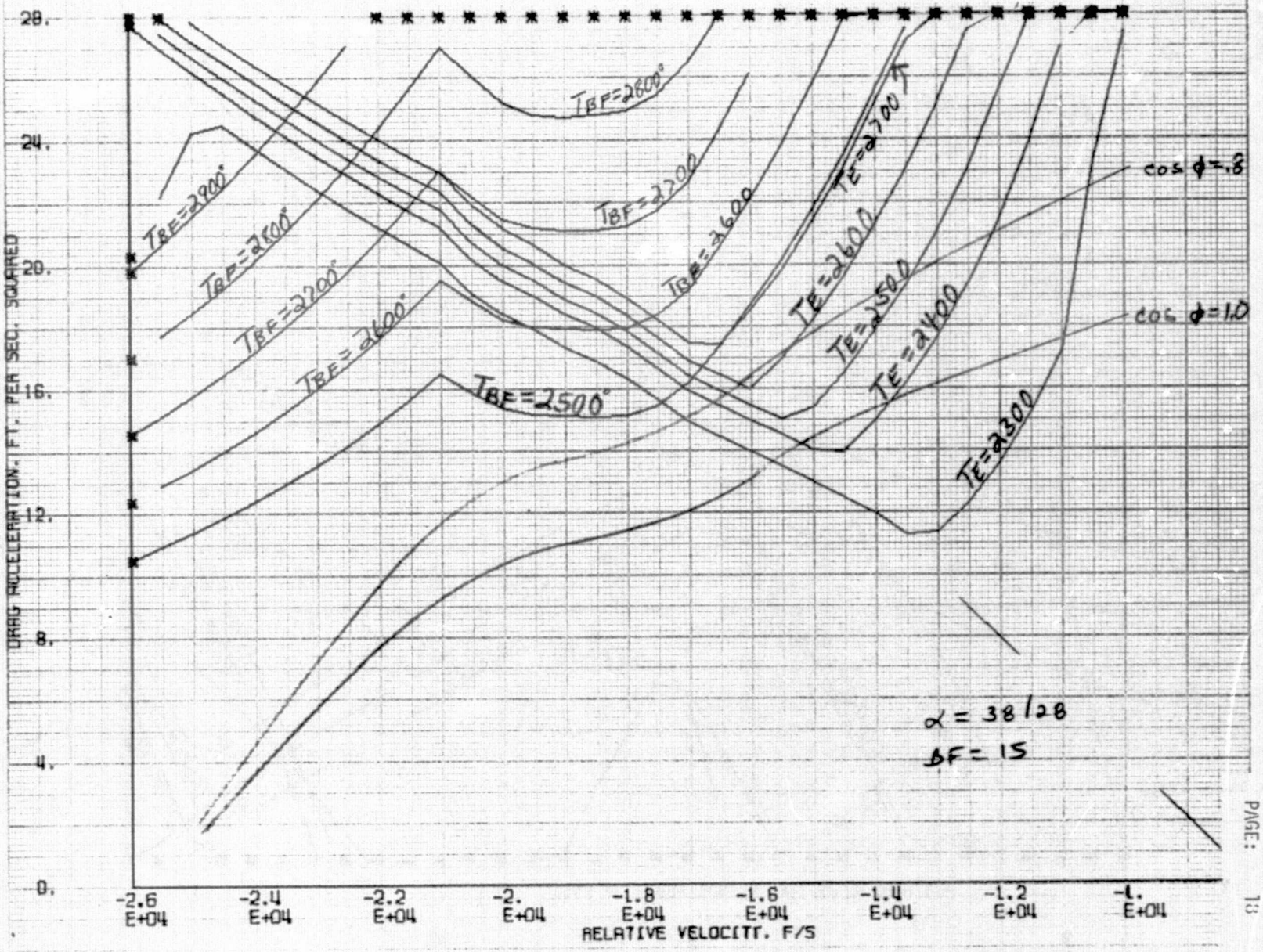

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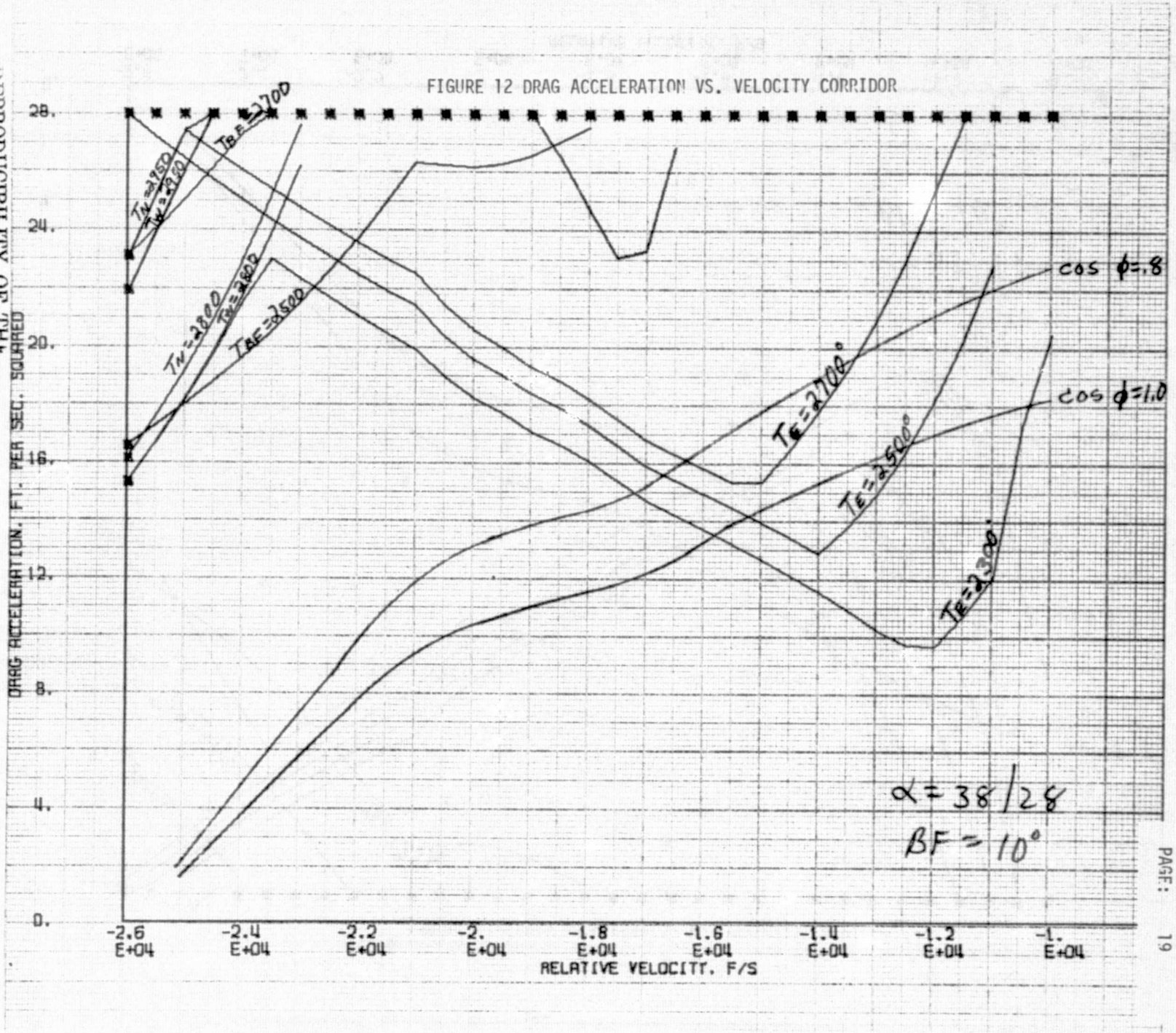

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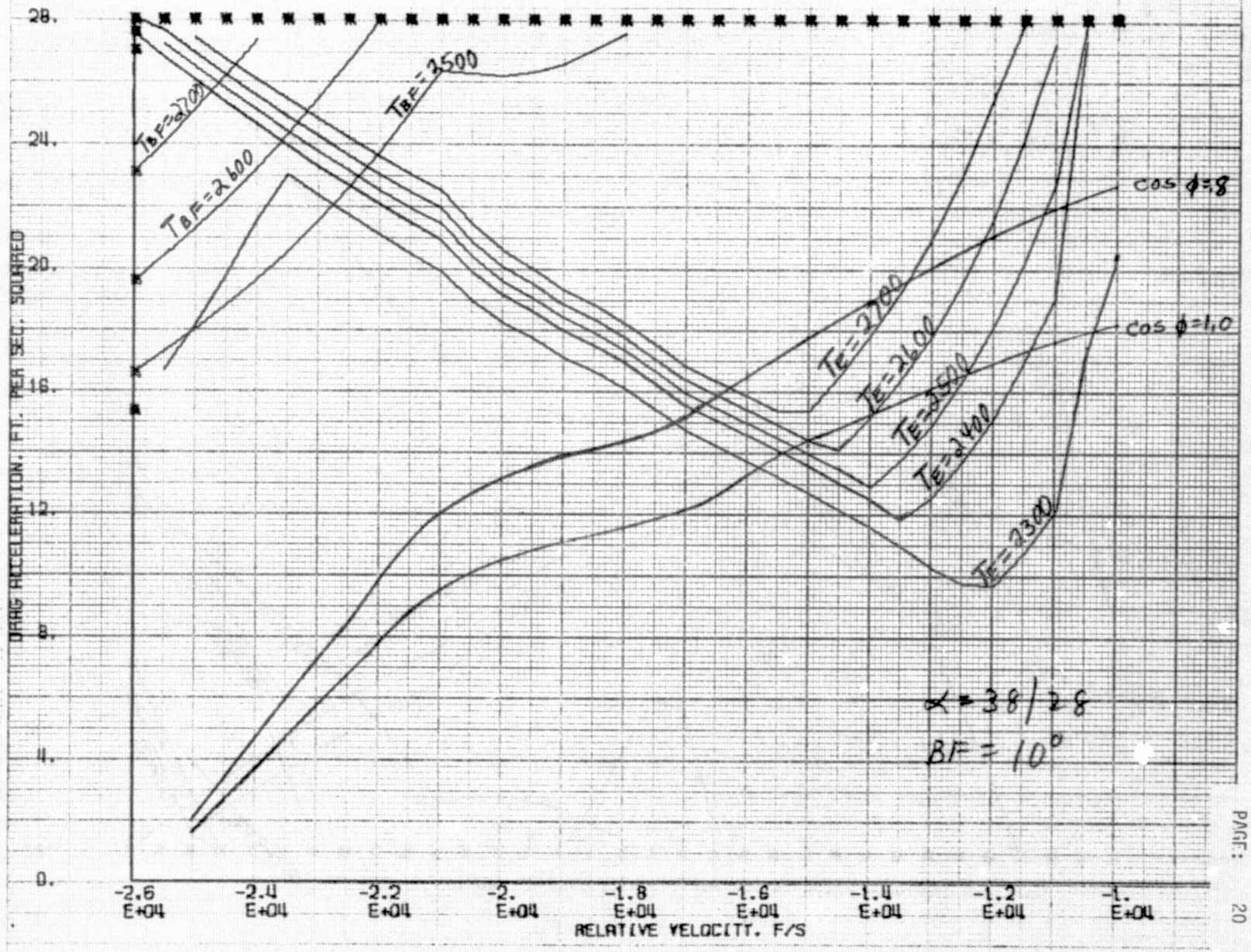

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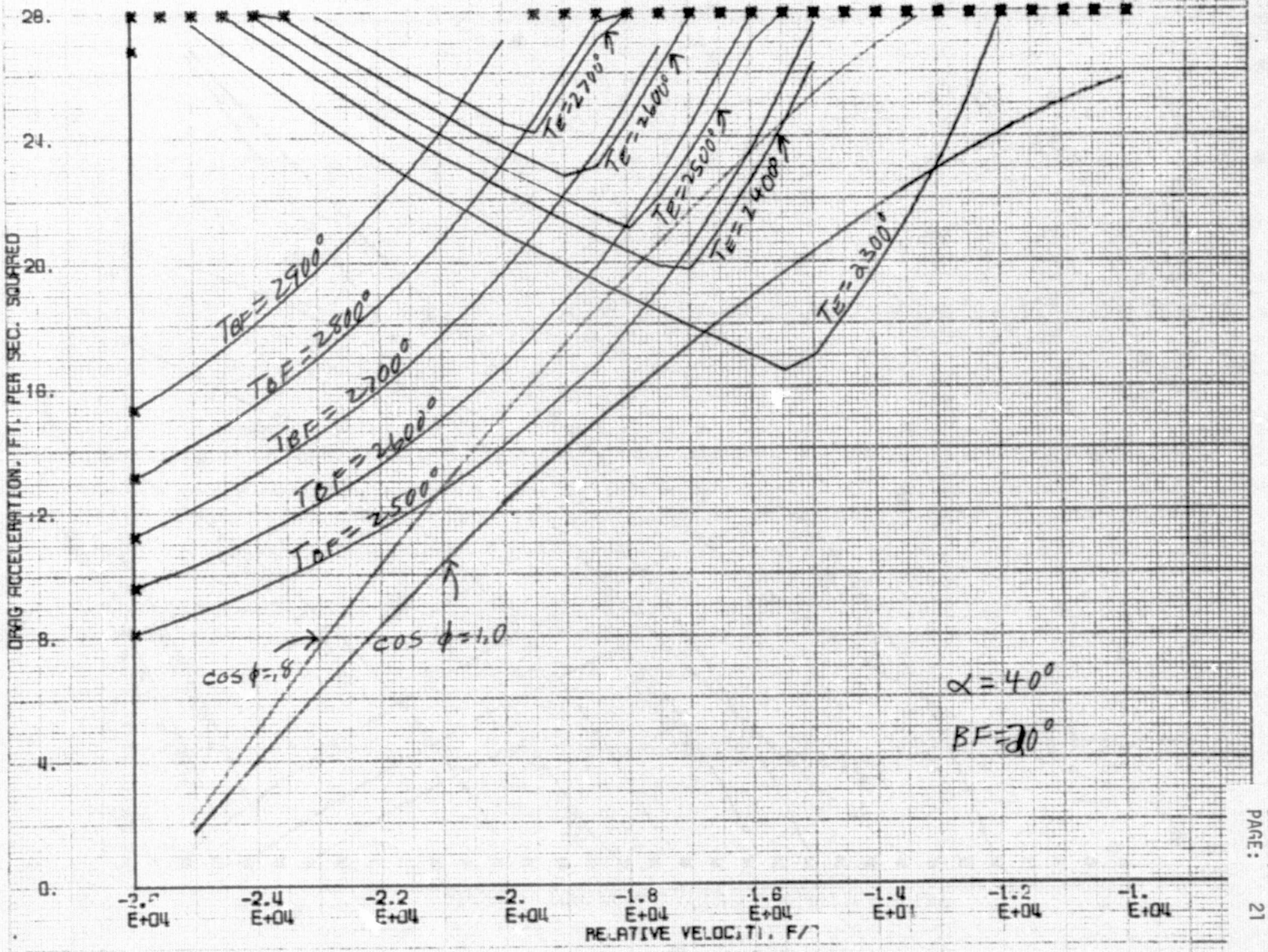

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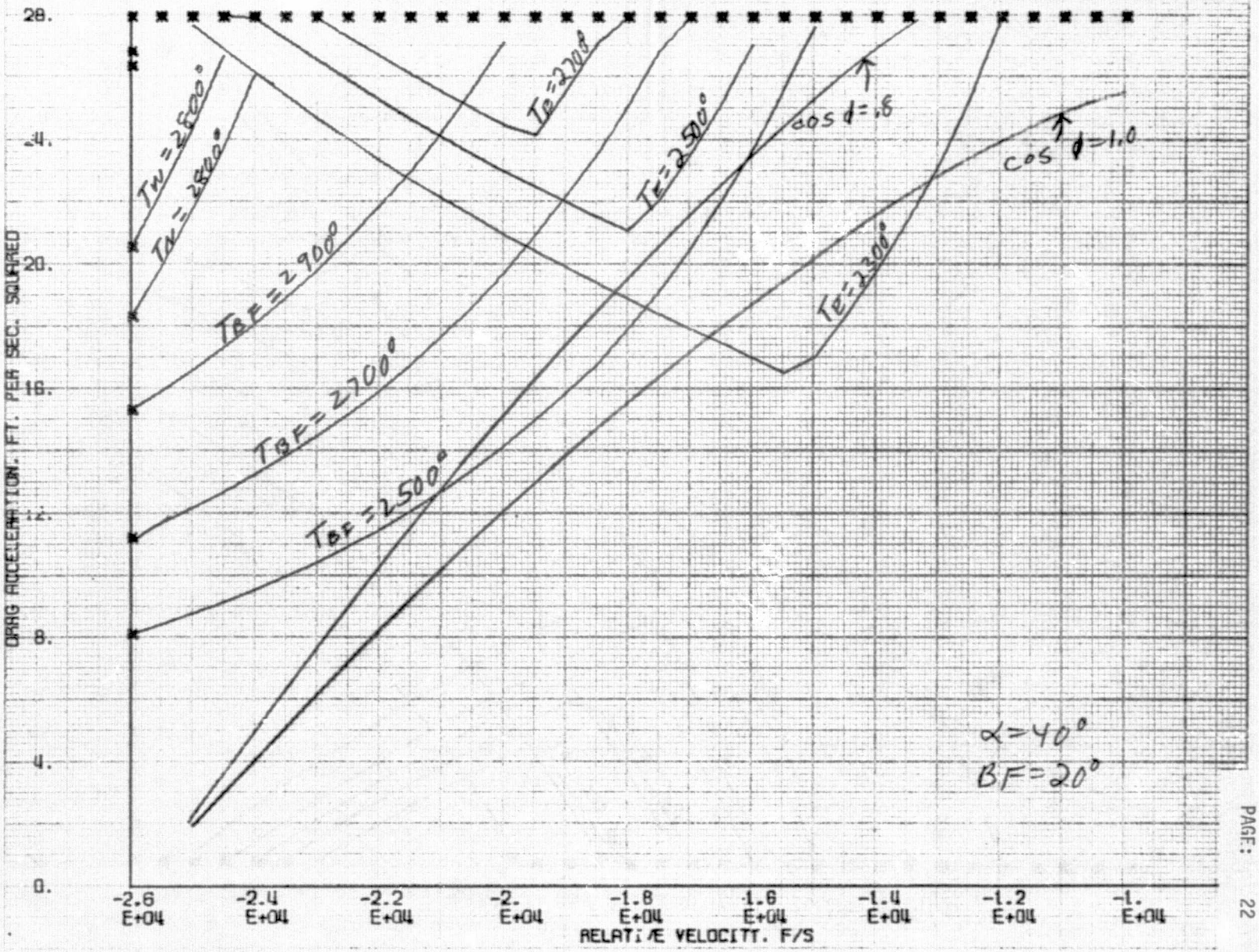

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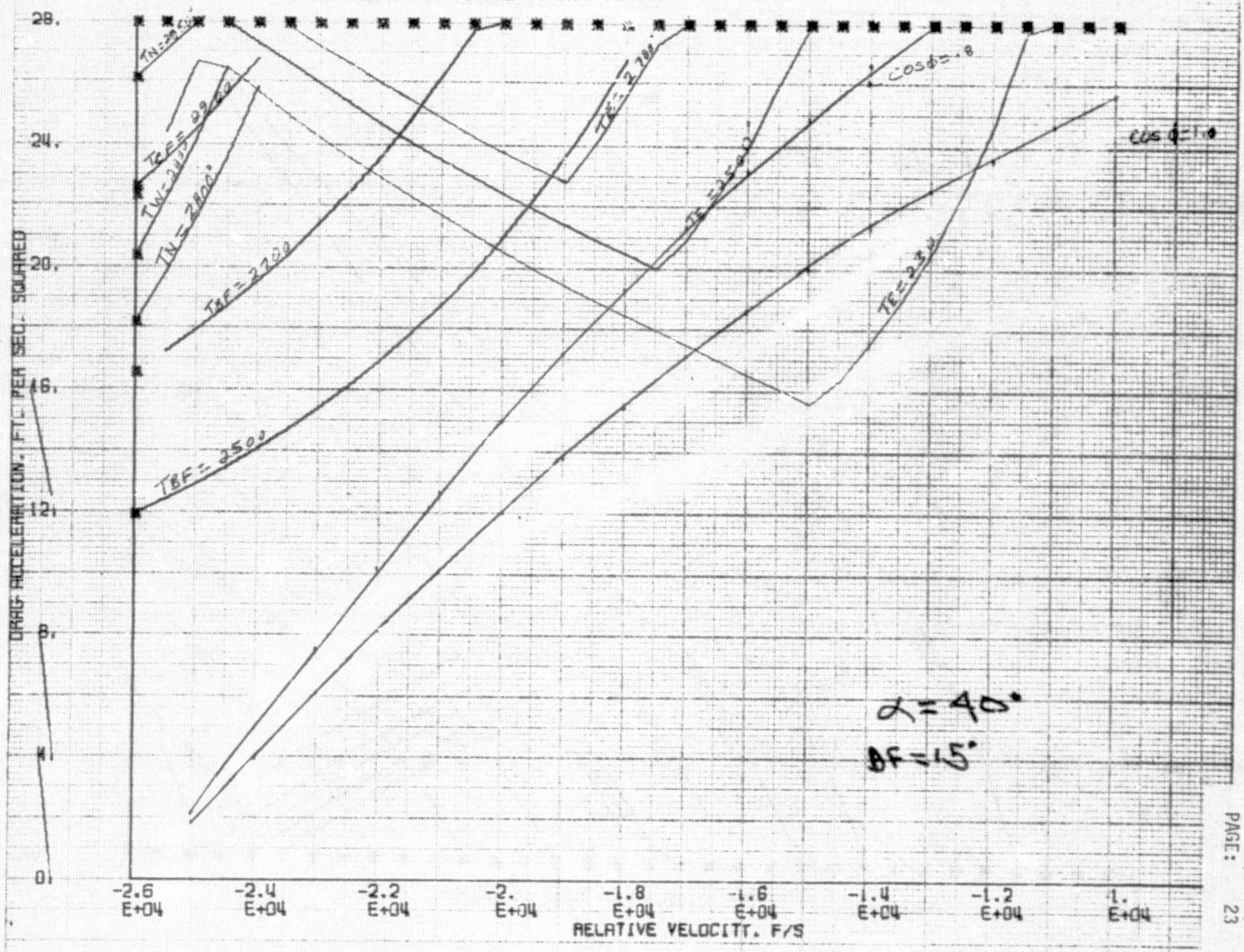

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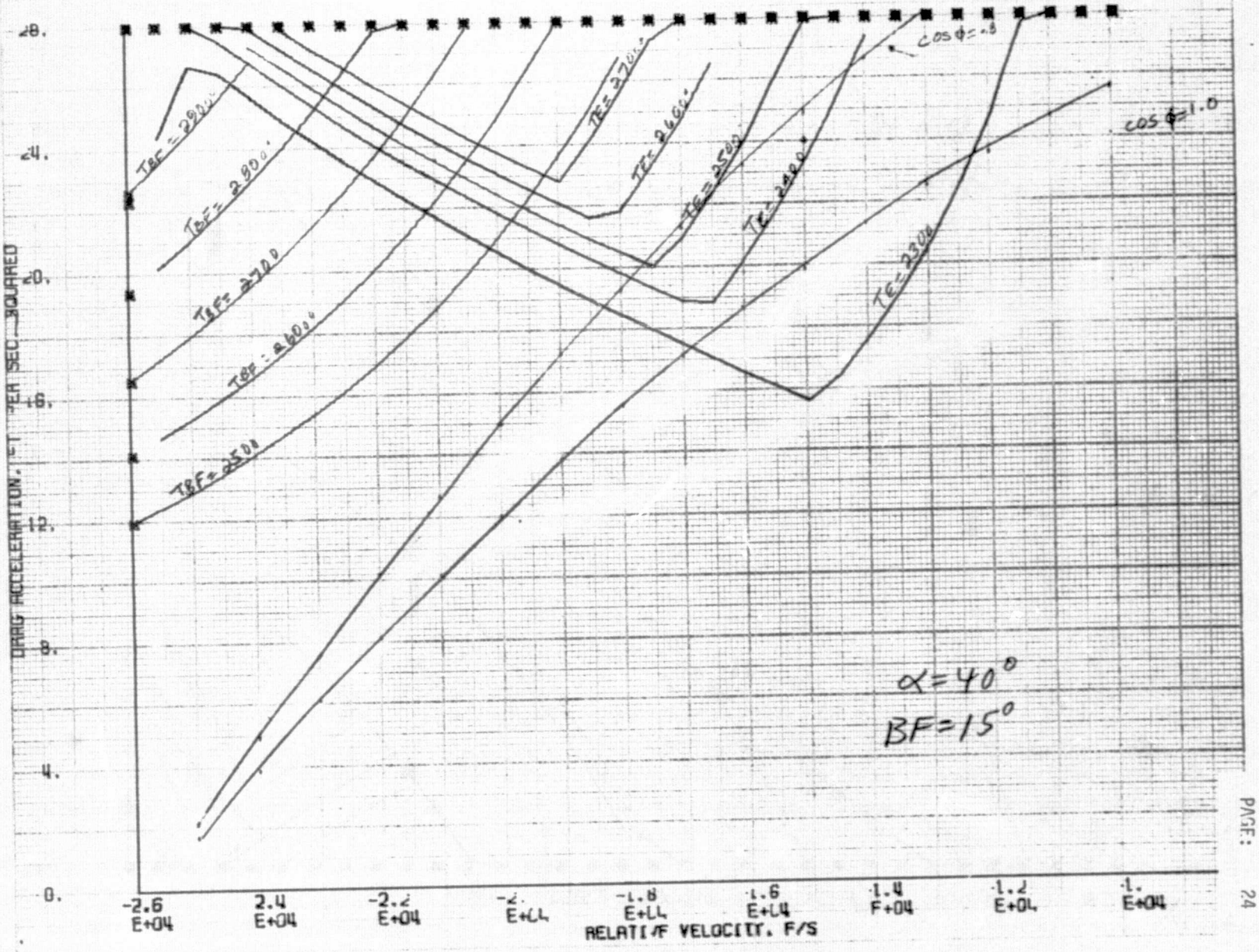

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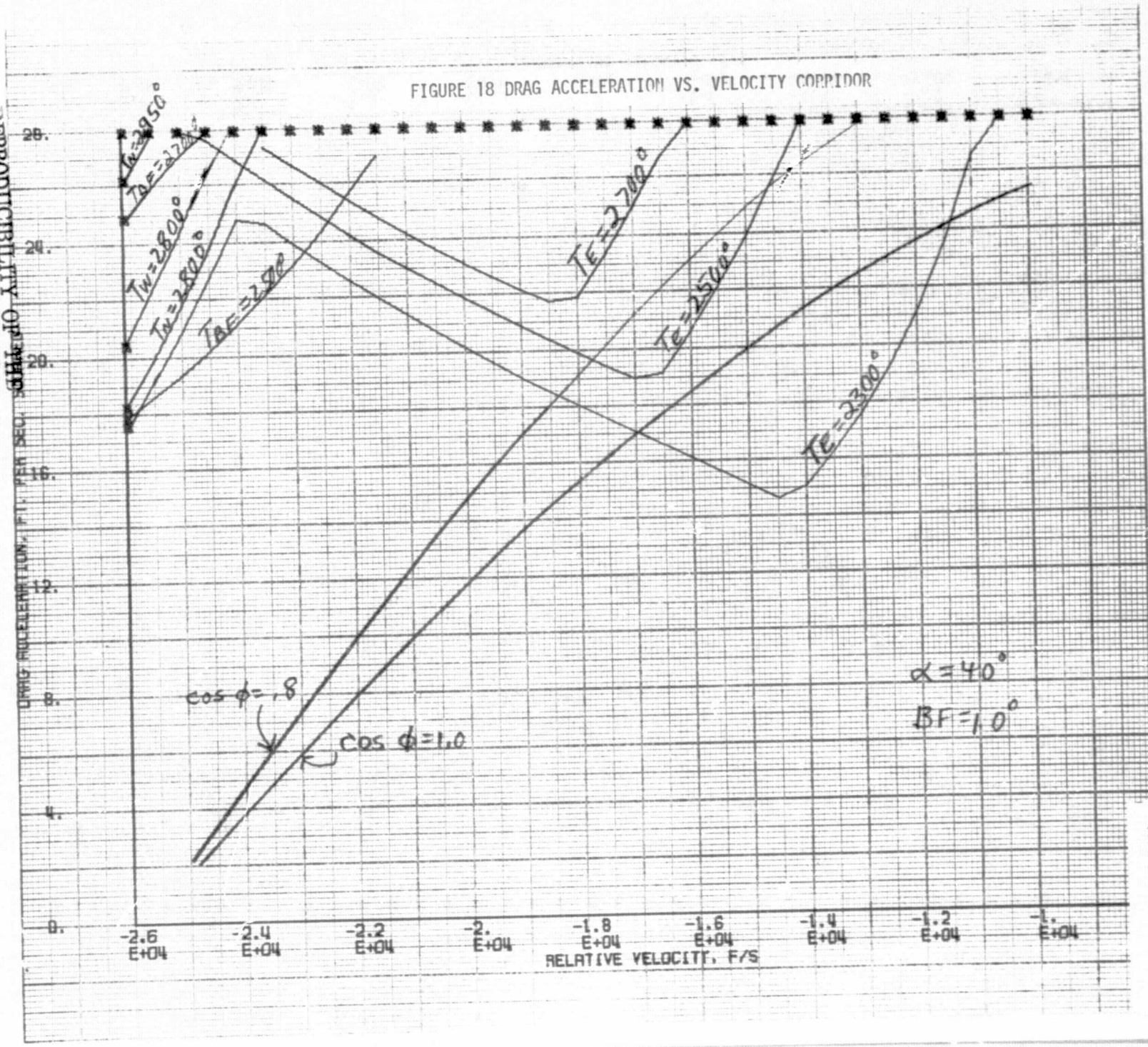

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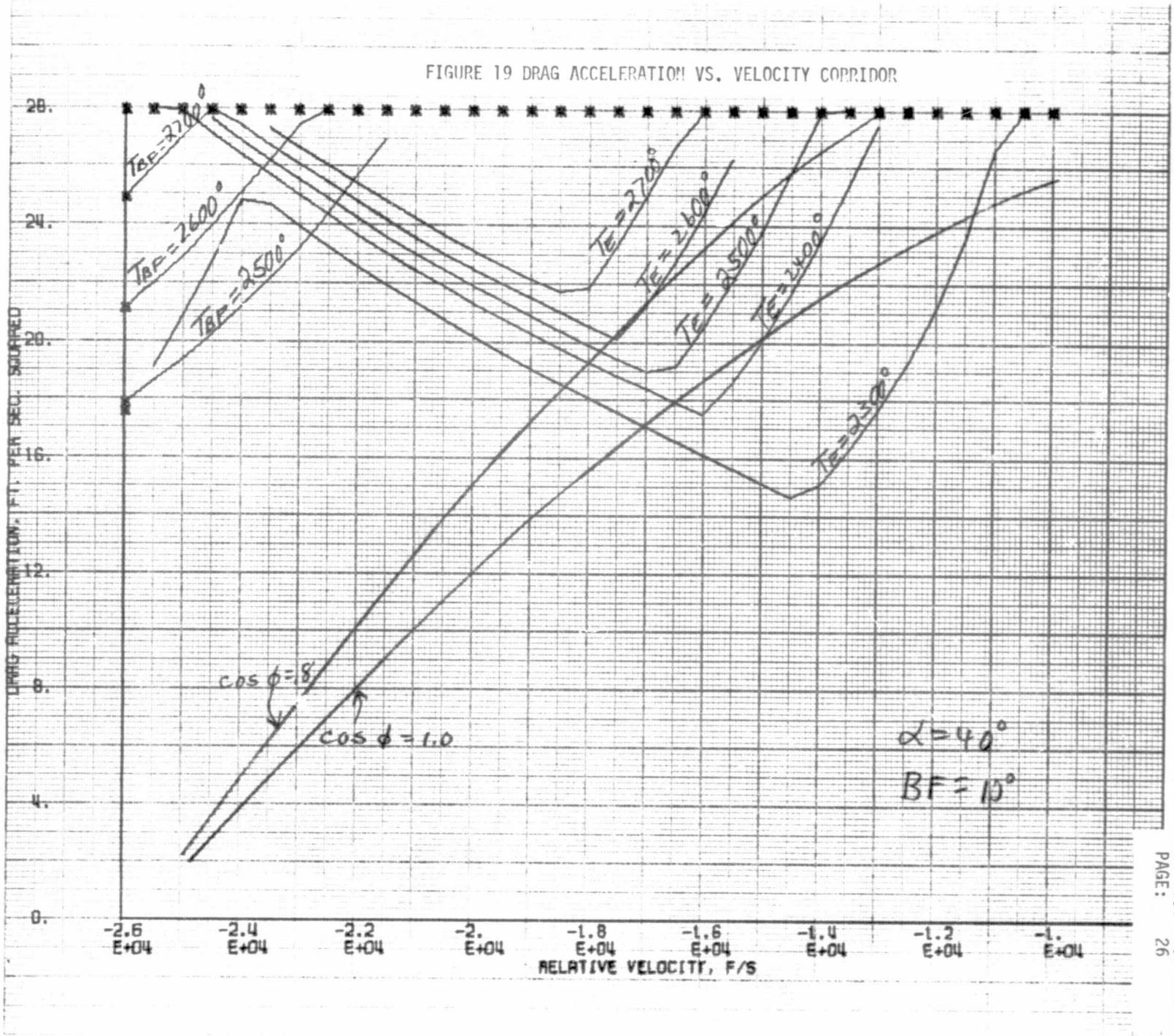

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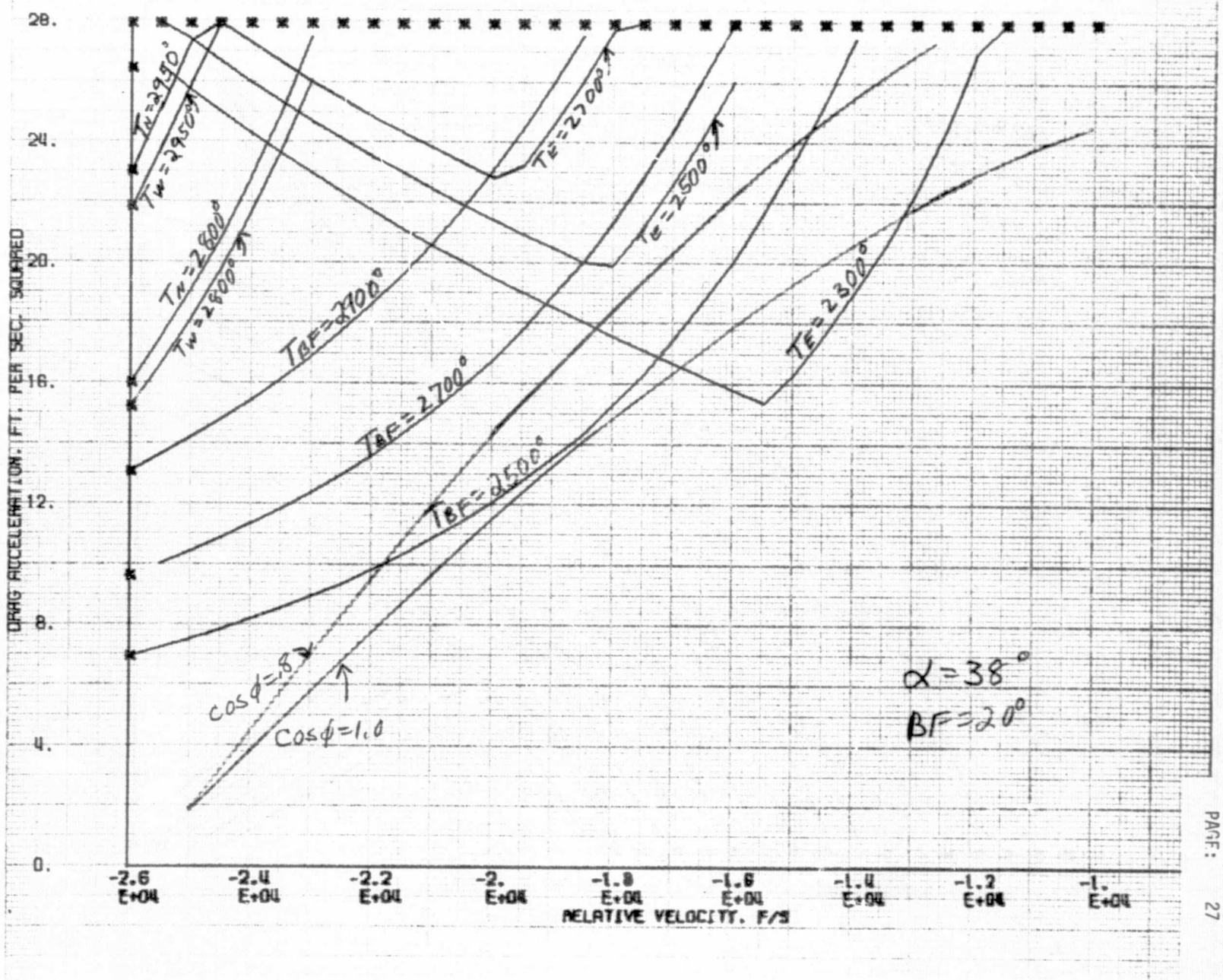

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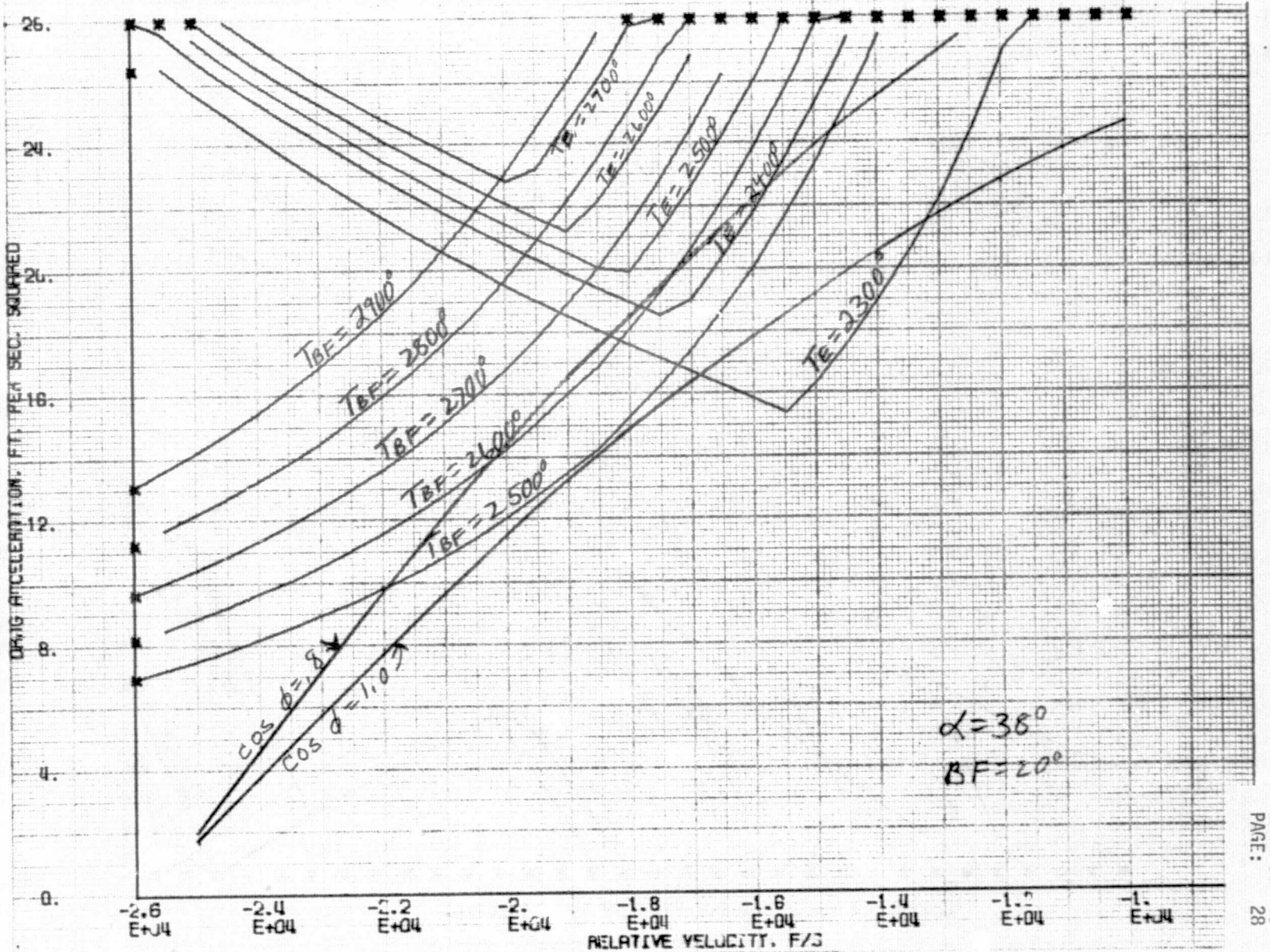

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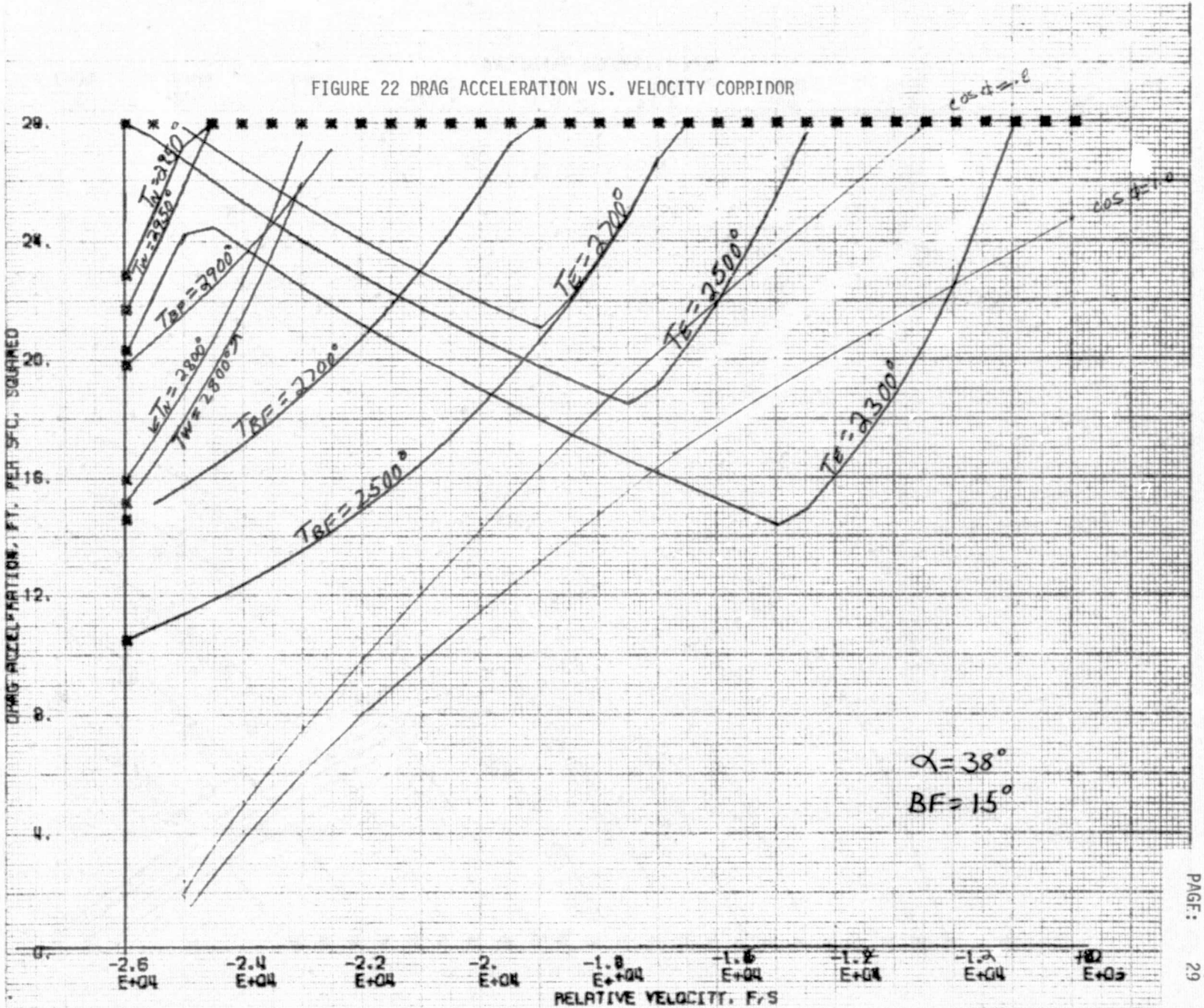

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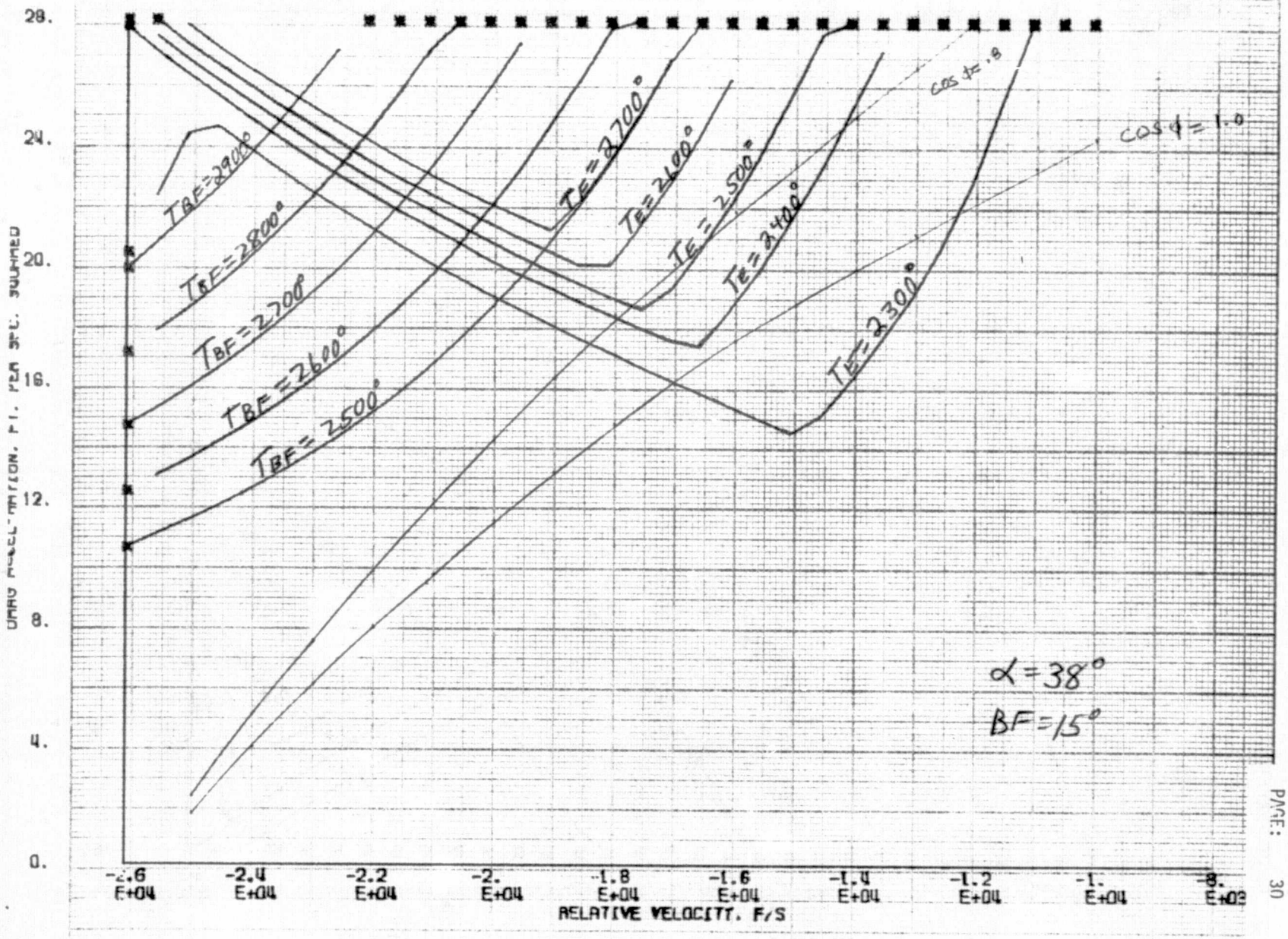

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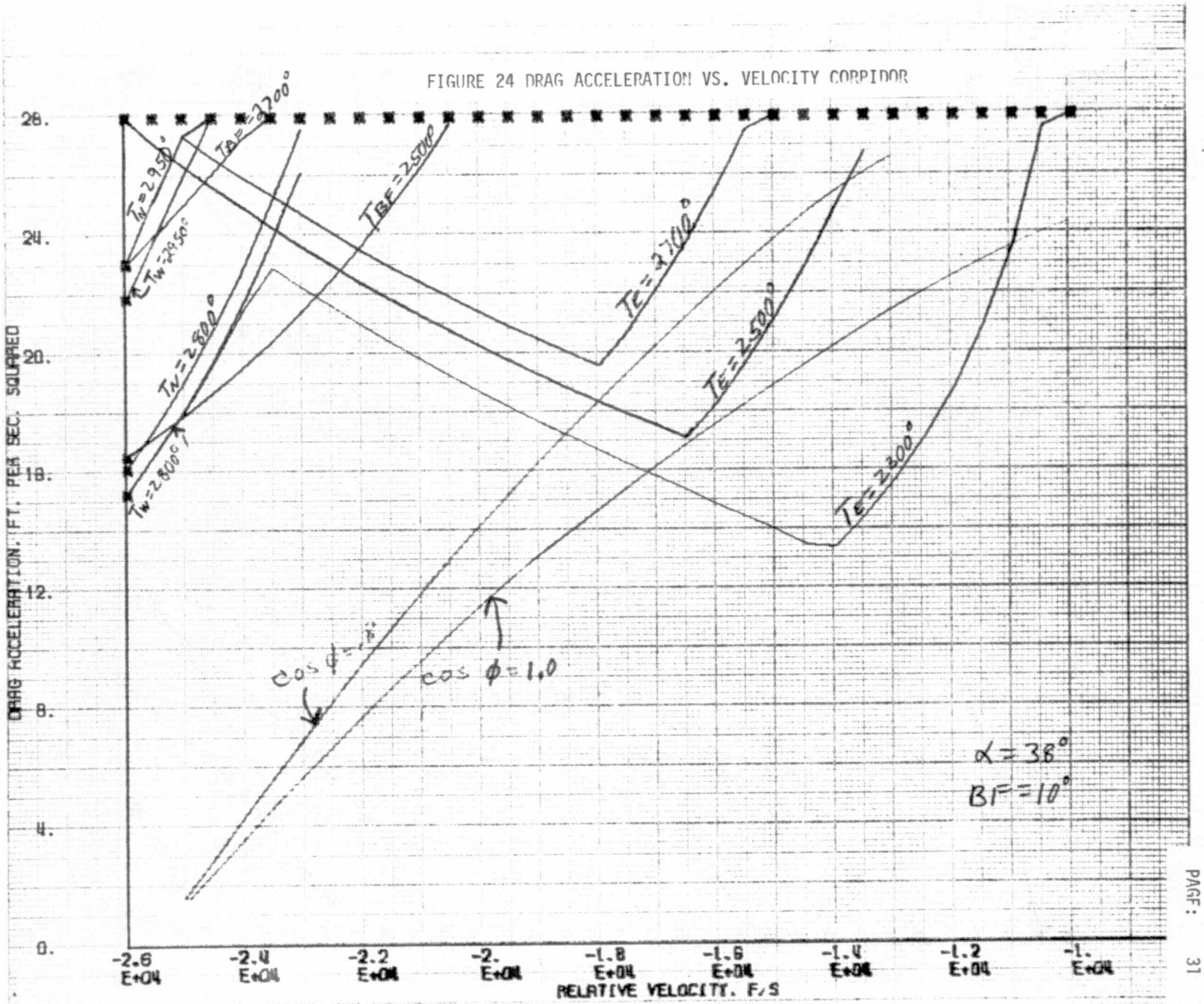

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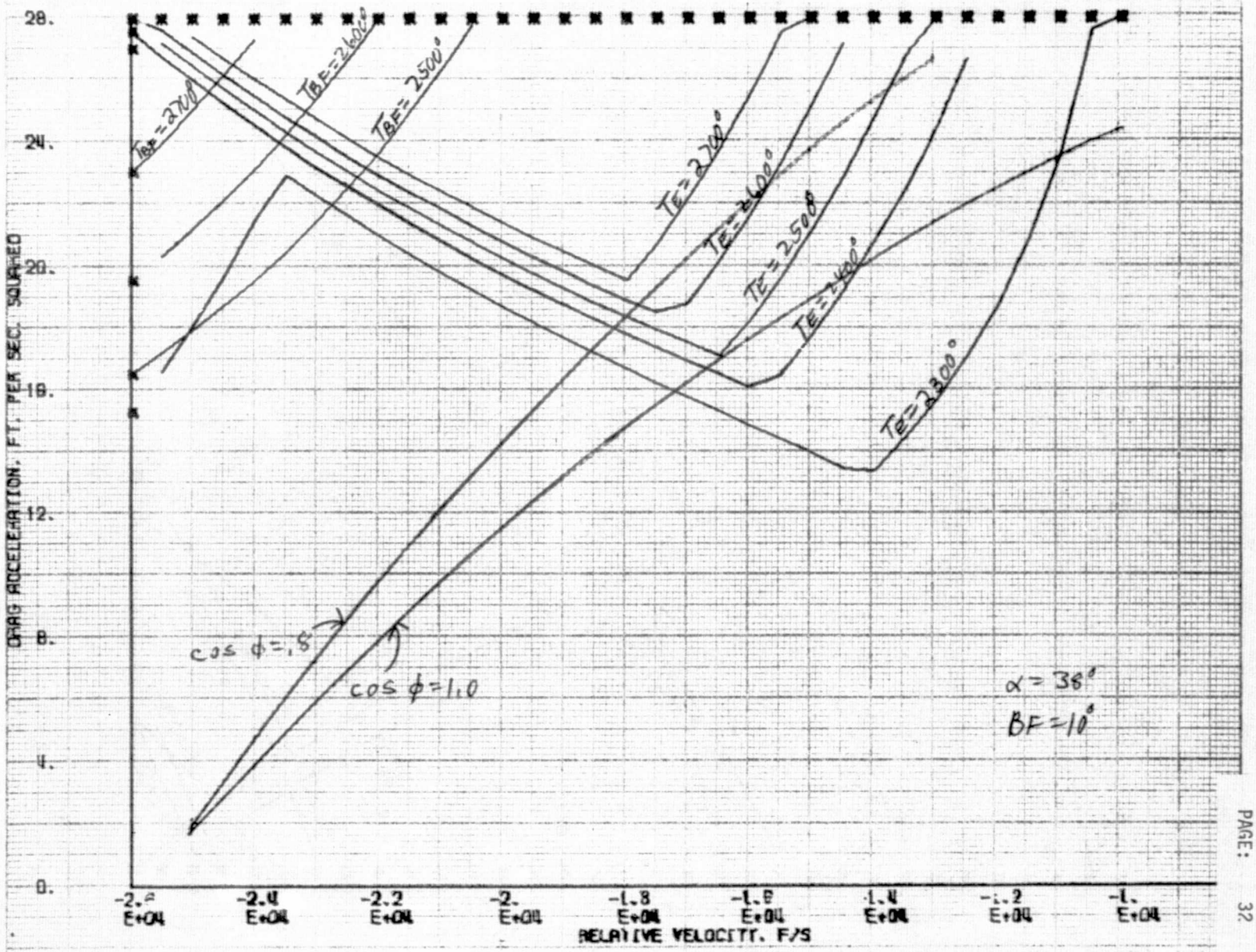

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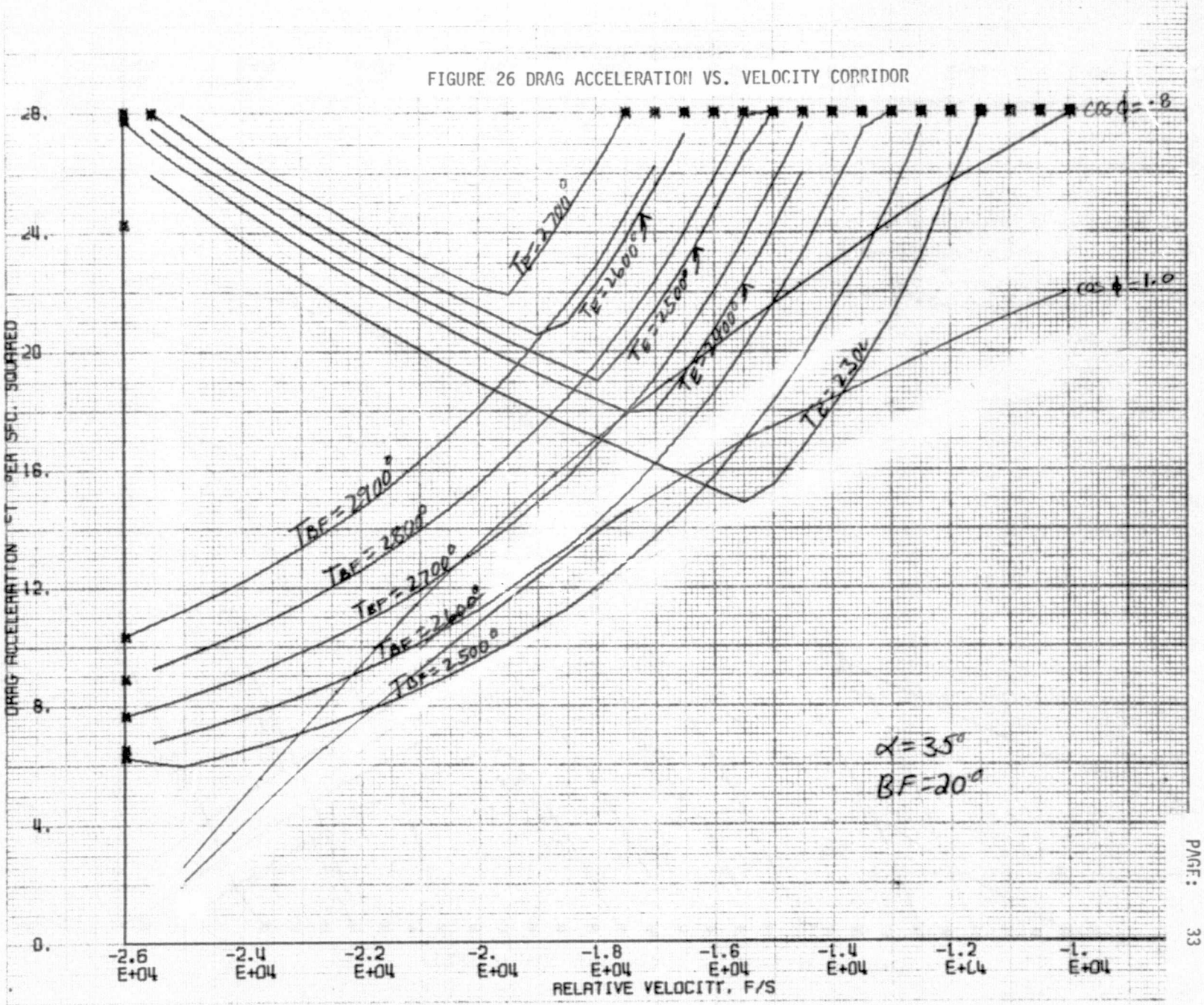

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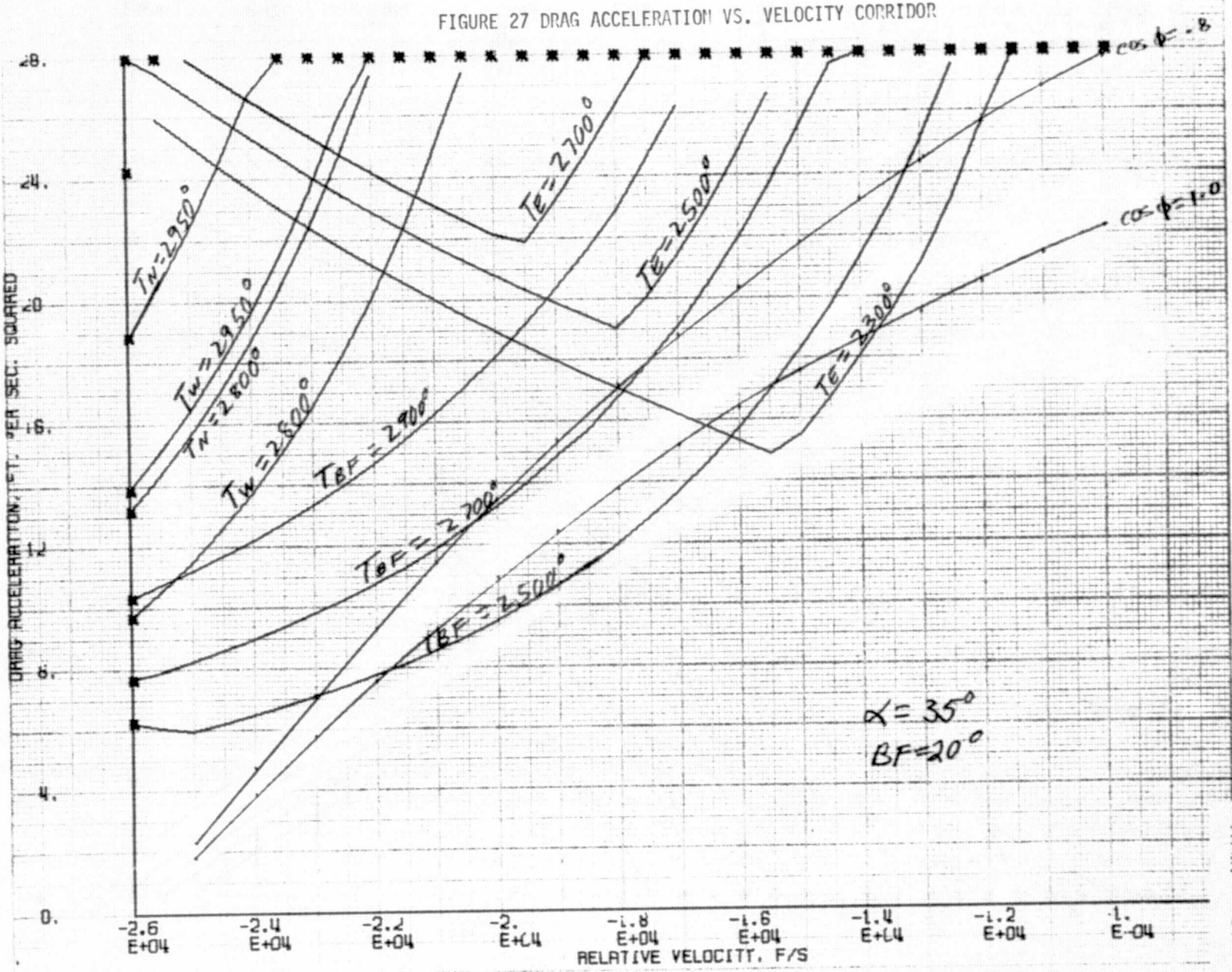

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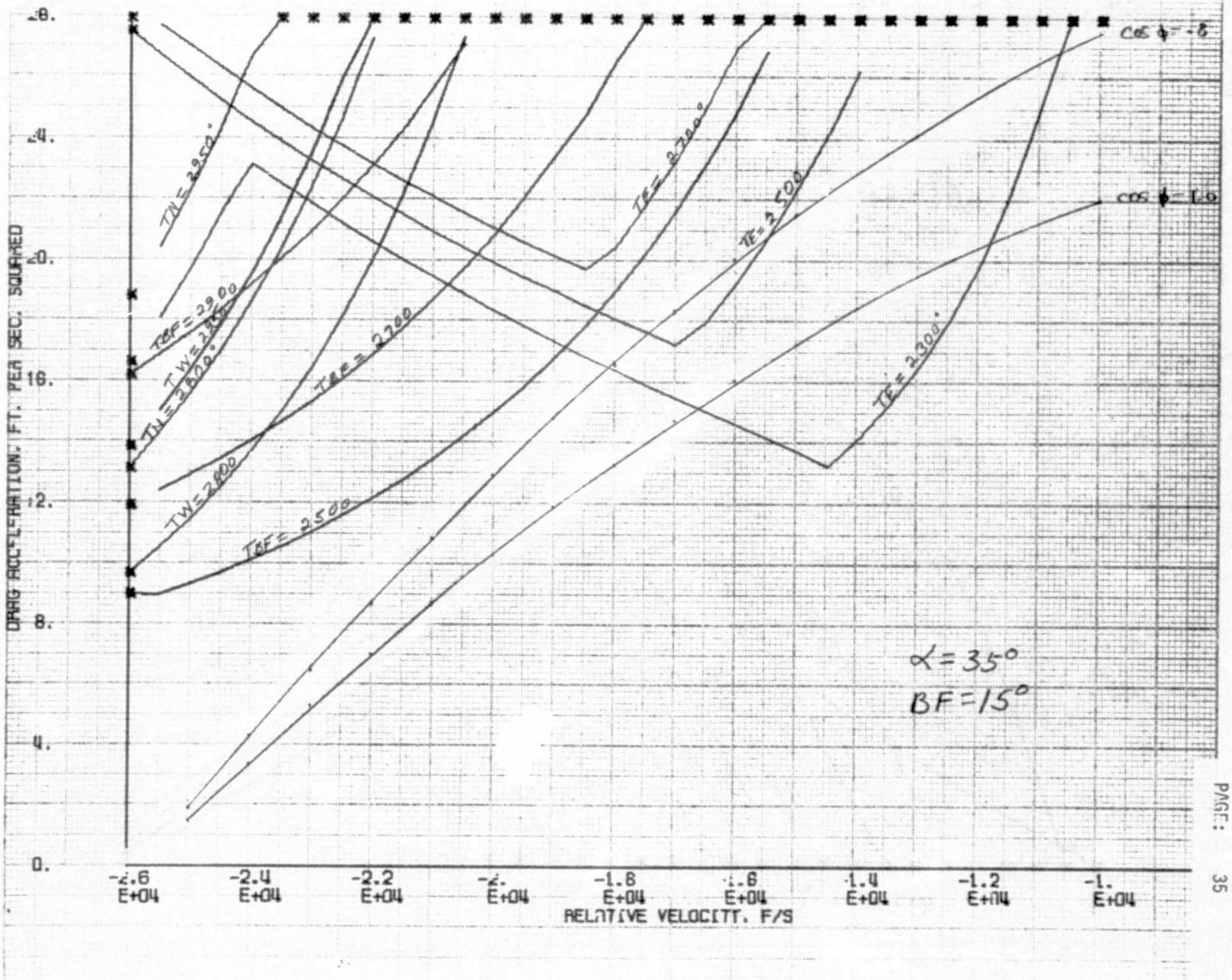

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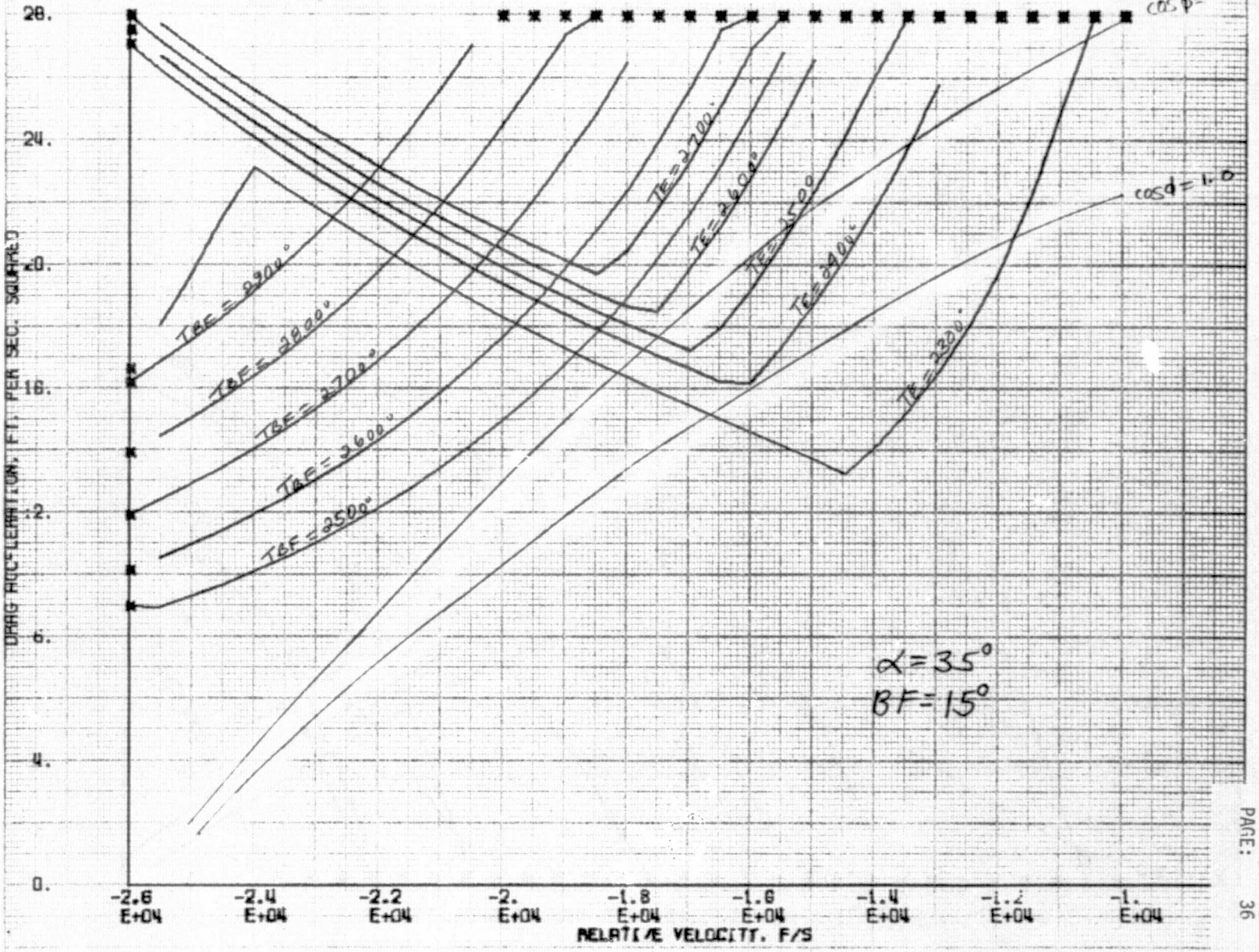

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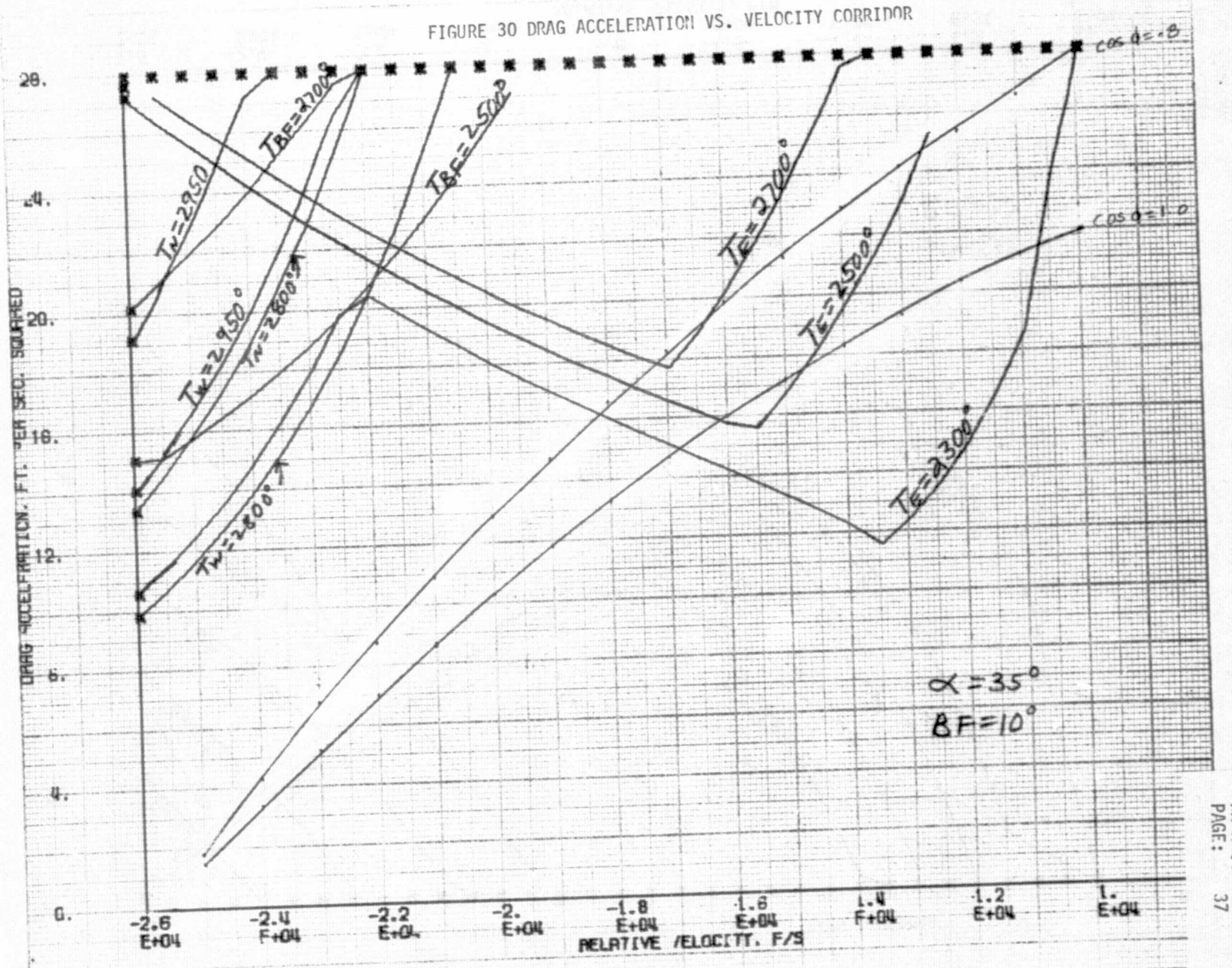

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FIGURE 31 DRAG ACCELERATION VS. VELOCITY CORRIDOR

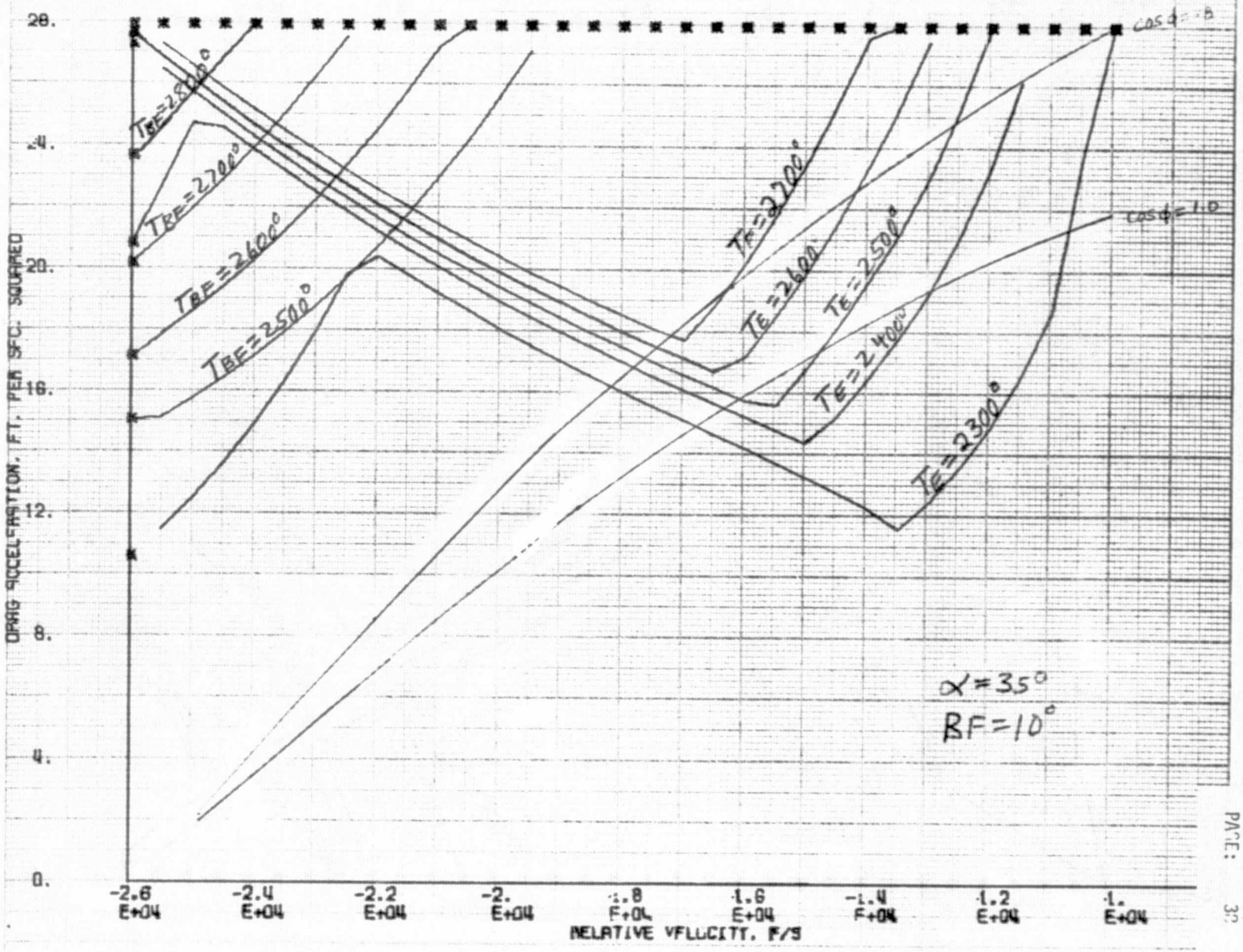

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FIGURE 32 DRAG ACCELERATION VS. VELOCITY CORRIDOR

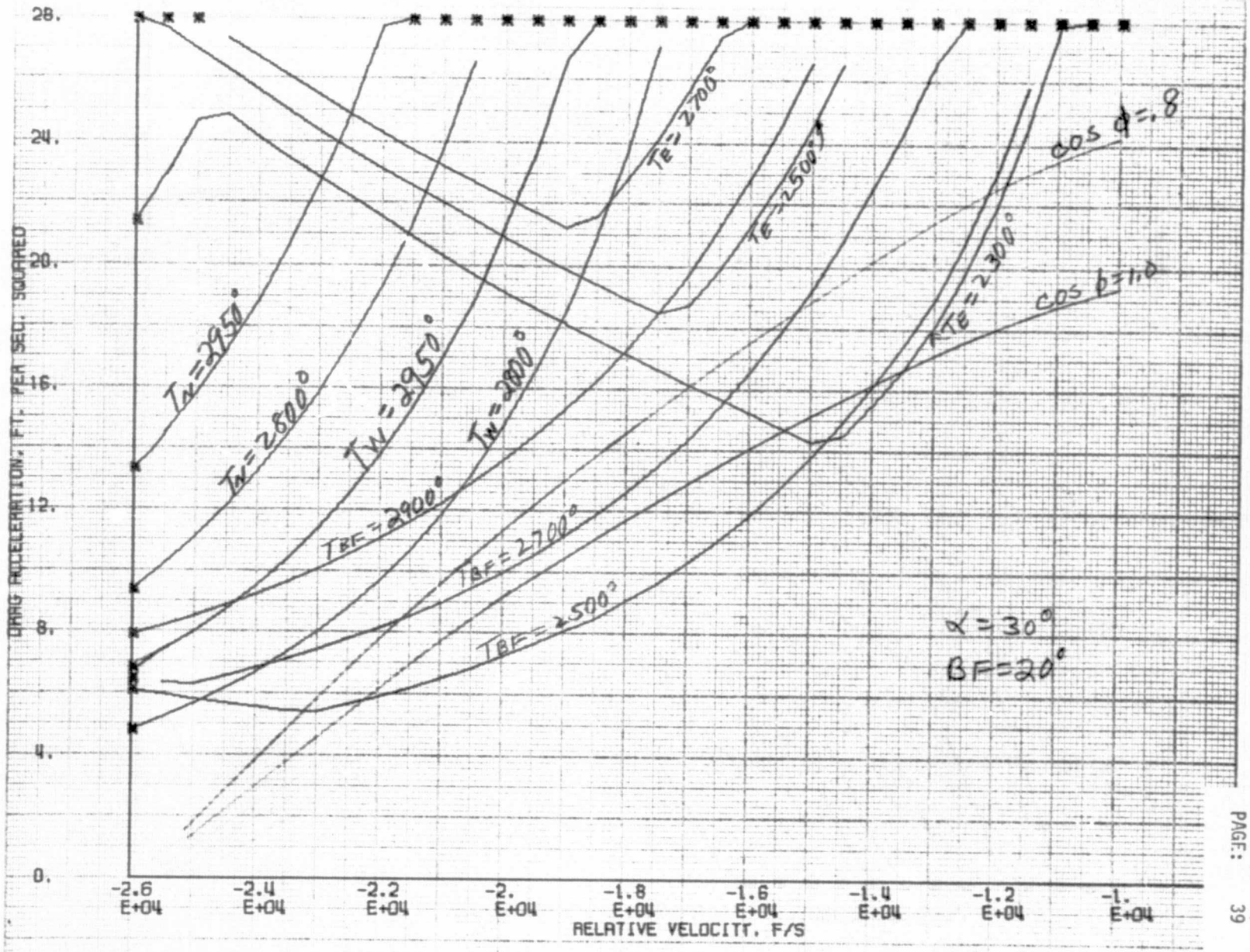

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FIGURE 33 DRAG ACCELERATION VS. VELOCITY CORRIDOR

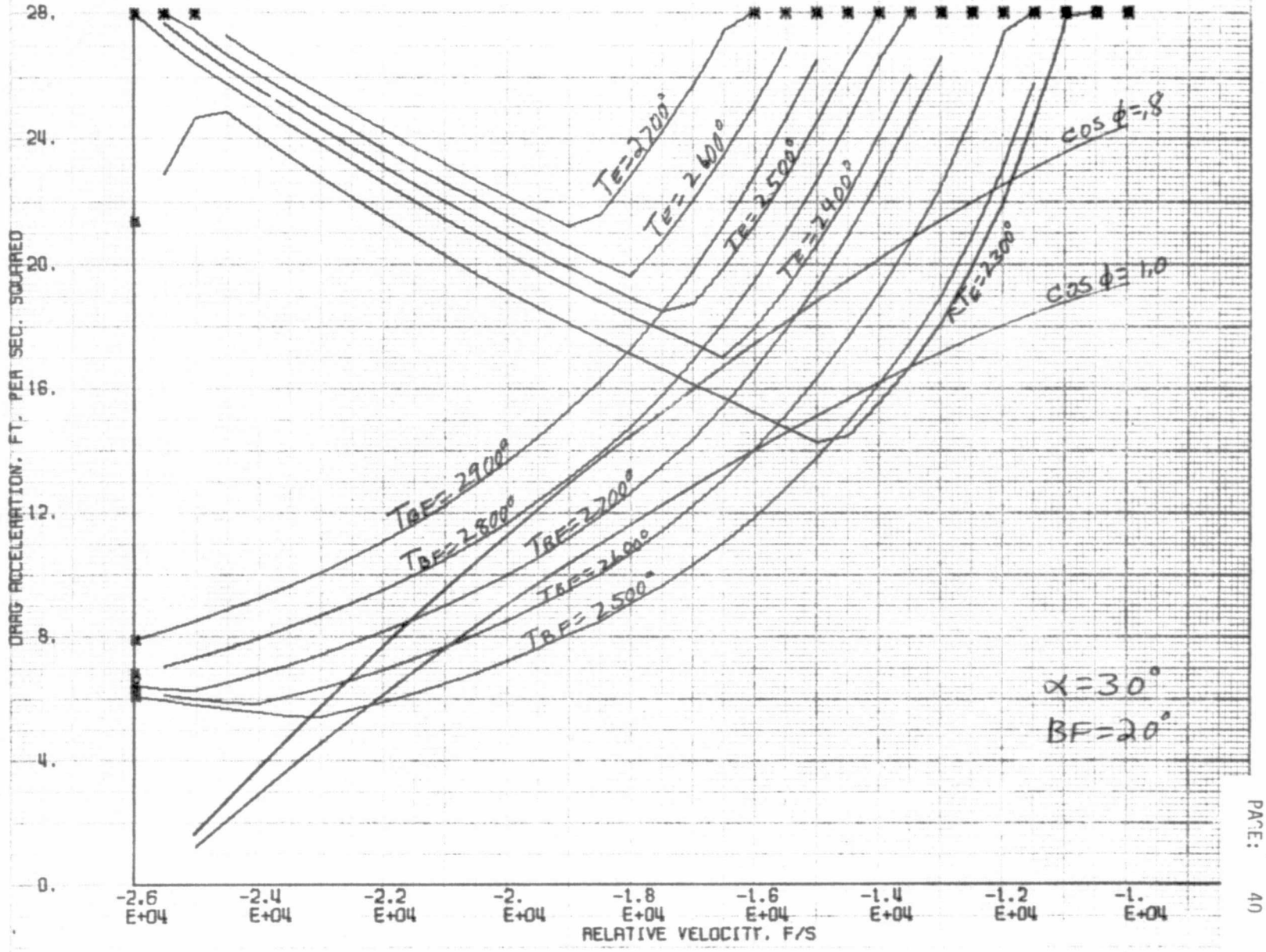

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FIGURE 34 DRAG ACCELERATION VS. VELOCITY CORRIDOR

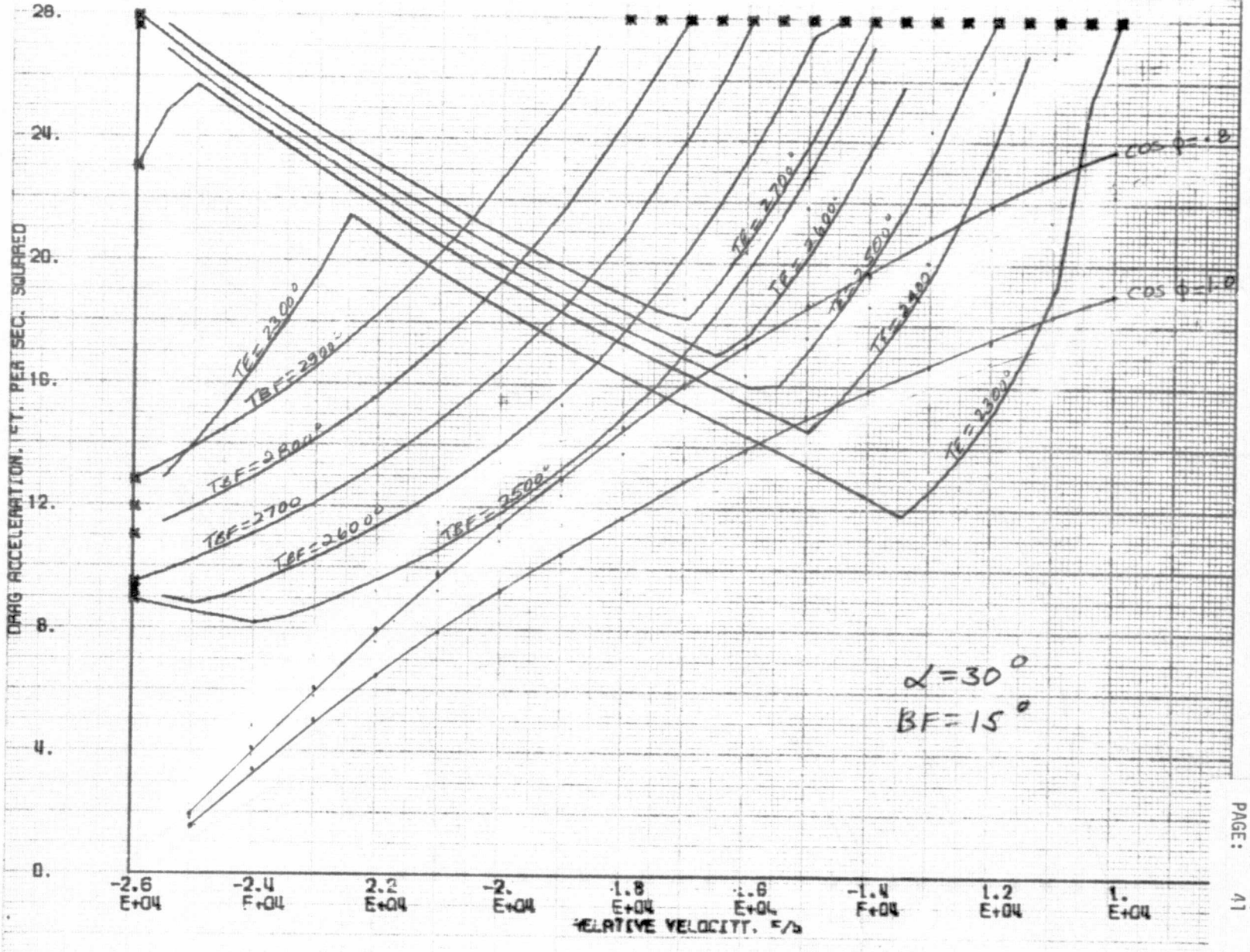

FIGURE 35 DRAG ACCELERATION VS. VELOCITY CORRIDOR

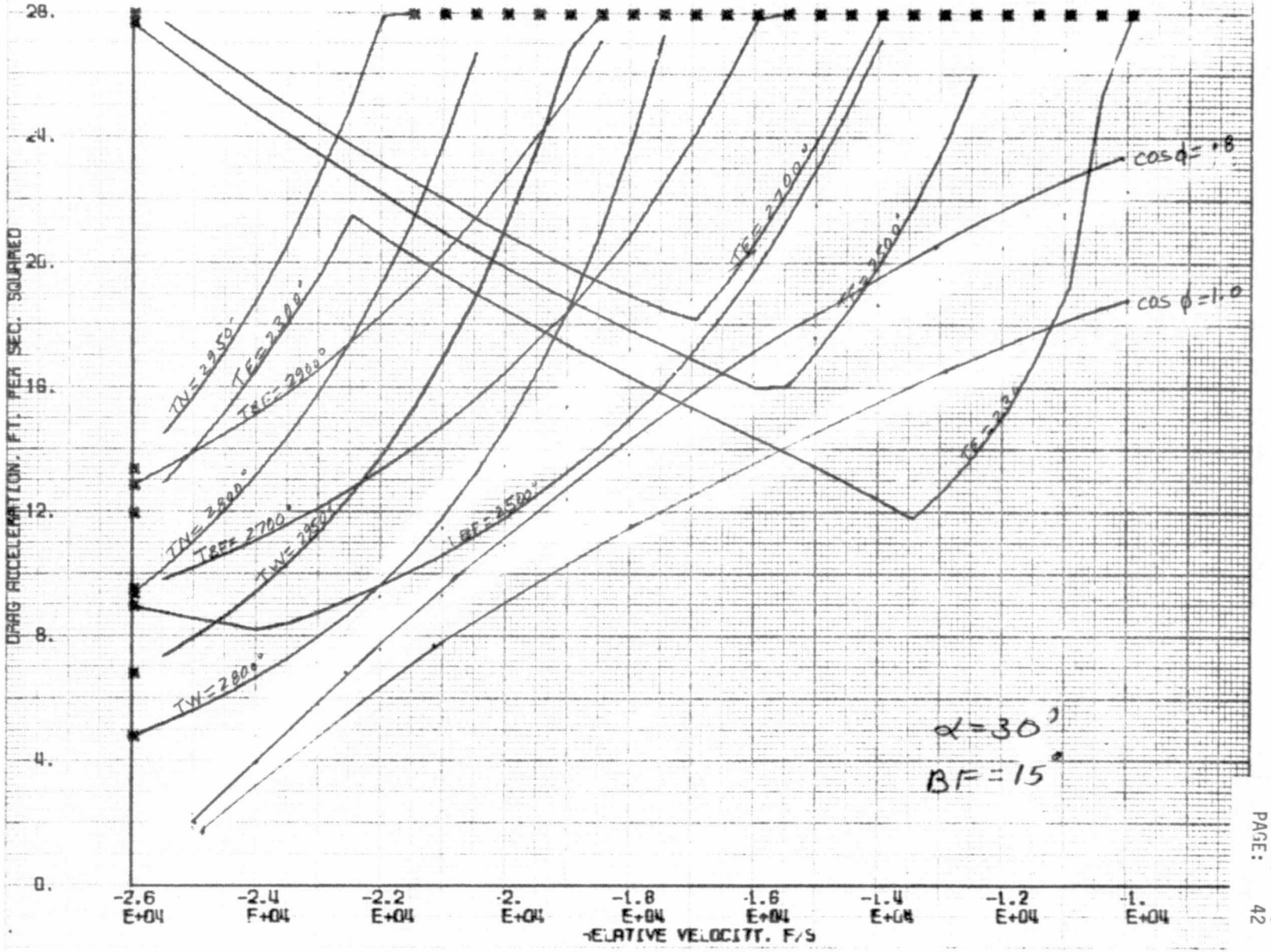

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FIGURE 36 DRAG ACCELERATION VS. VELOCITY CORRIDOR

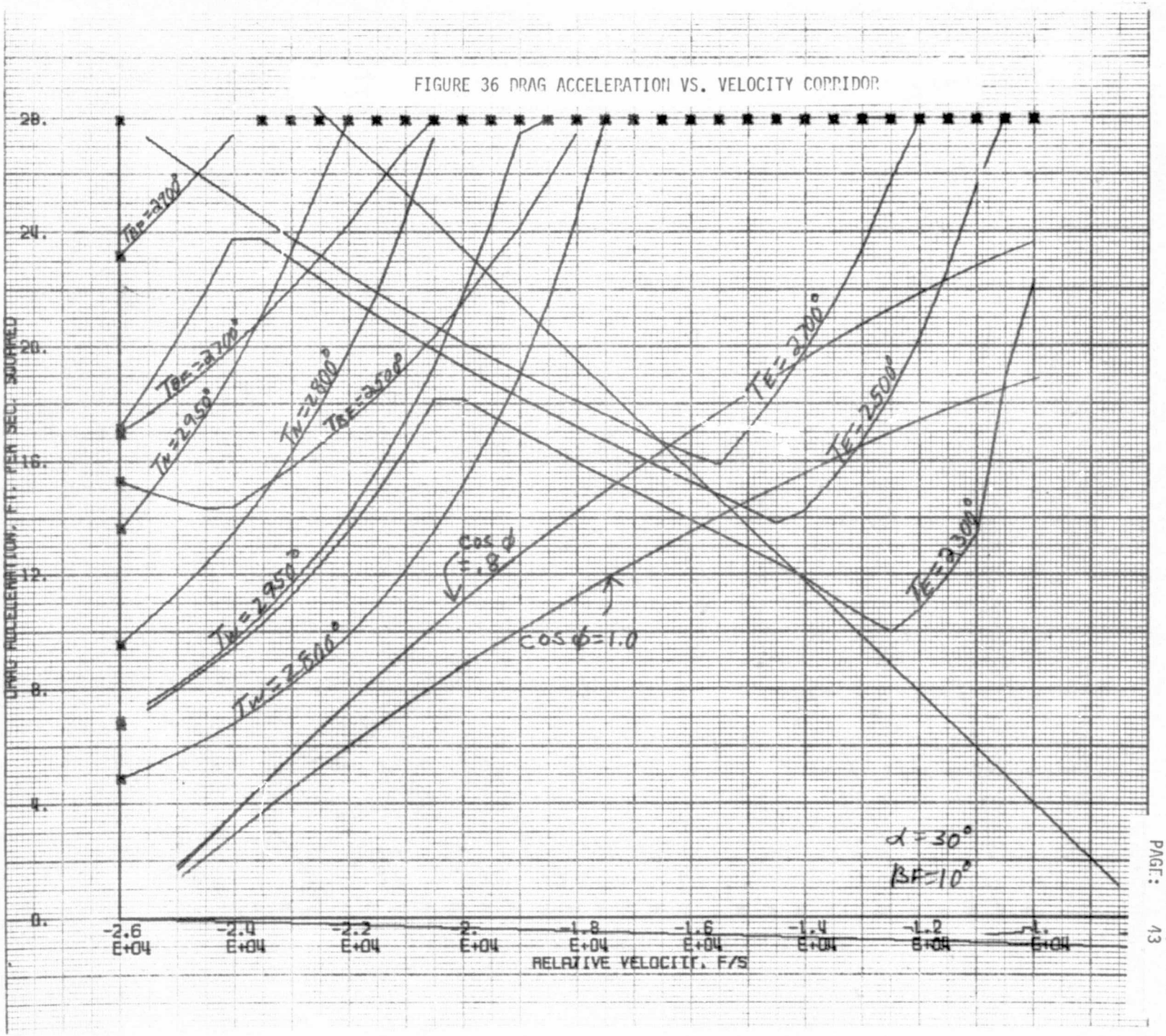

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FIGURE 37 DRAG ACCELERATION VS. VELOCITY CORRIDOR

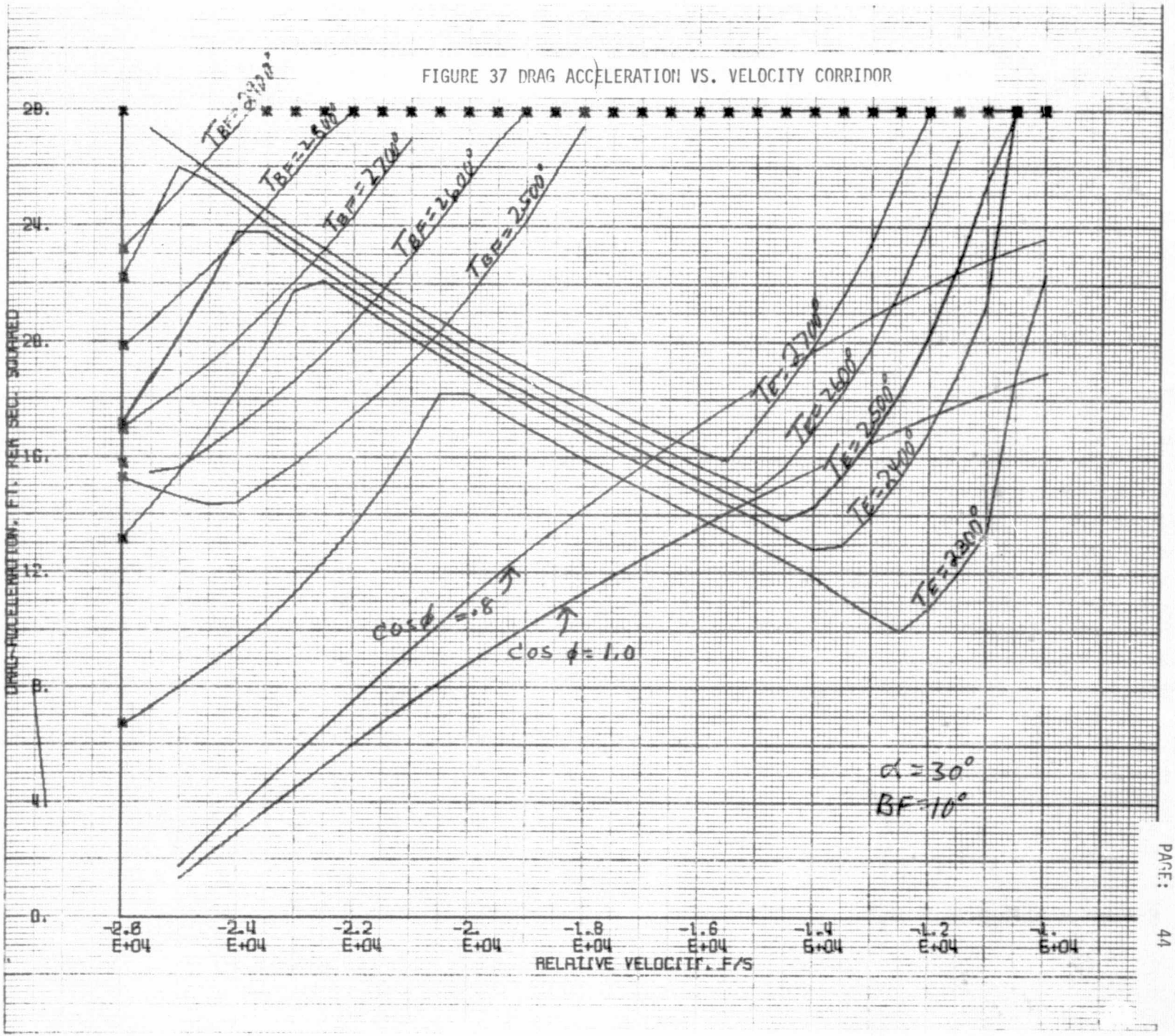

FIGURE 38 DRAG ACCELERATION VS. VELOCITY CORRIDOR

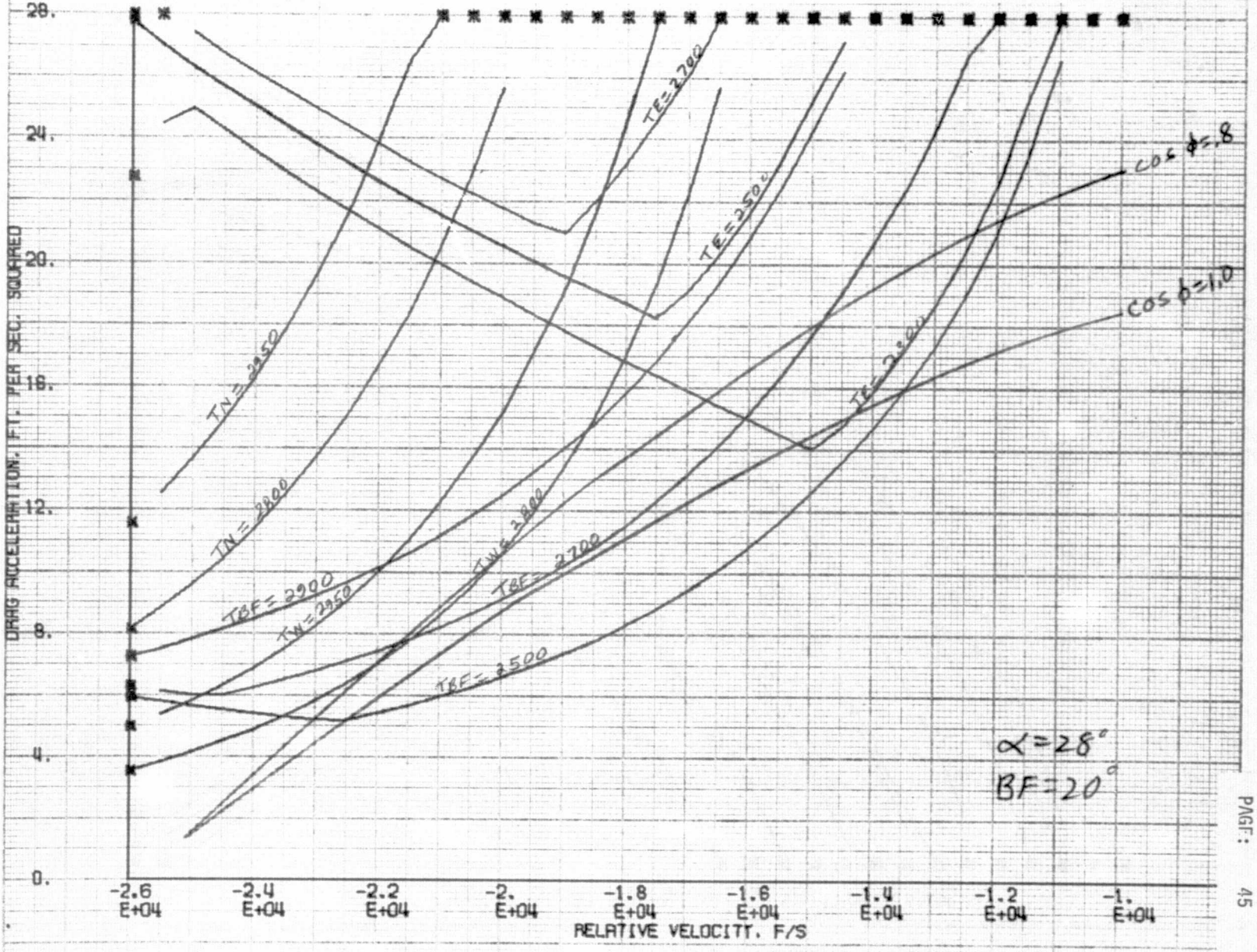

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FIGURE 39 DRAG ACCELERATION VS. VELOCITY CORRIDOR

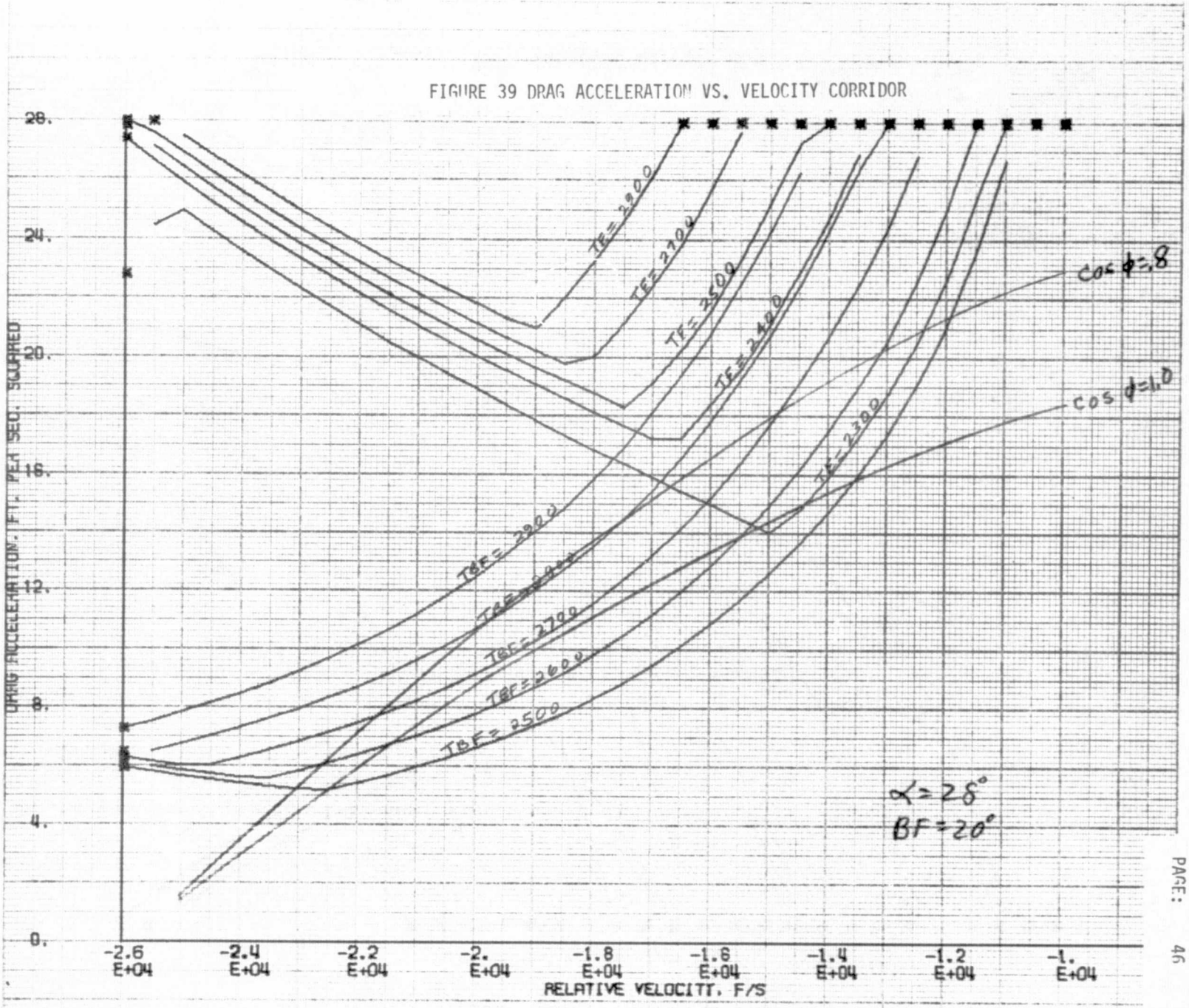

FIGURE 40 DRAG ACCELERATION VS. VELOCITY CORRIDOR

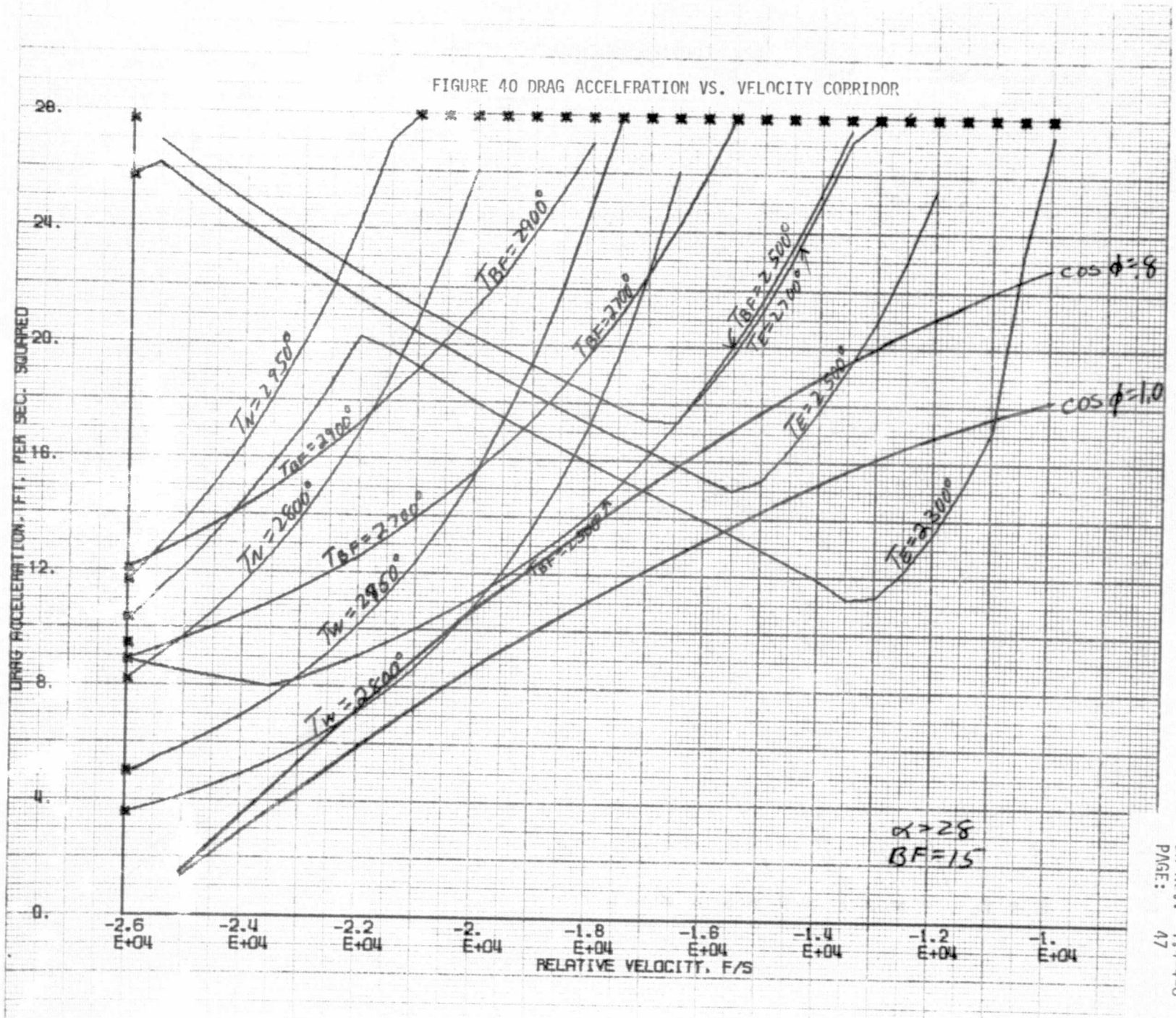

FIGURE 41 DRAG ACCELERATION VS. VELOCITY CORRIDOR

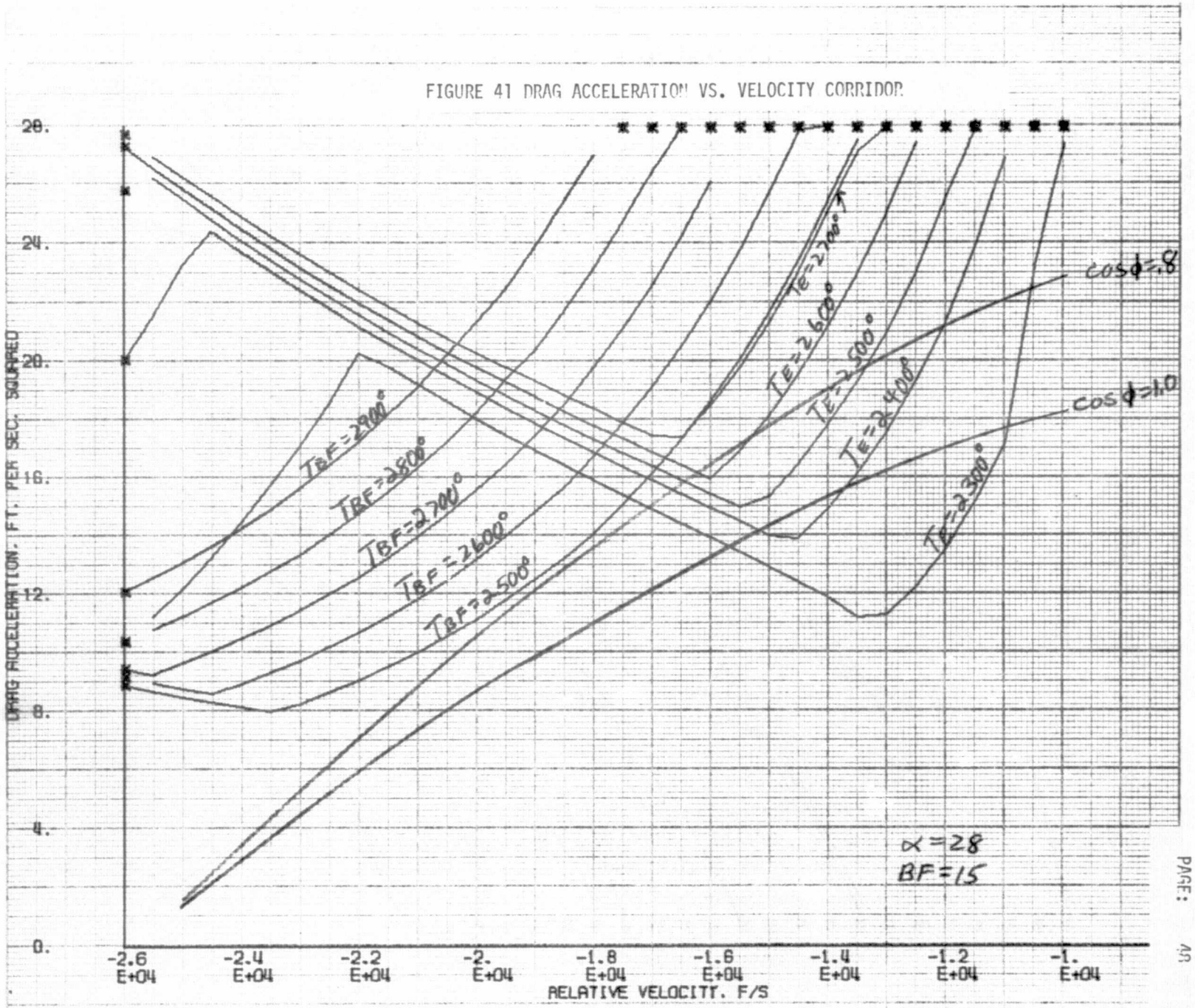

FIGURE 42 DRAG ACCELERATION VS. VELOCITY CORRIDOR

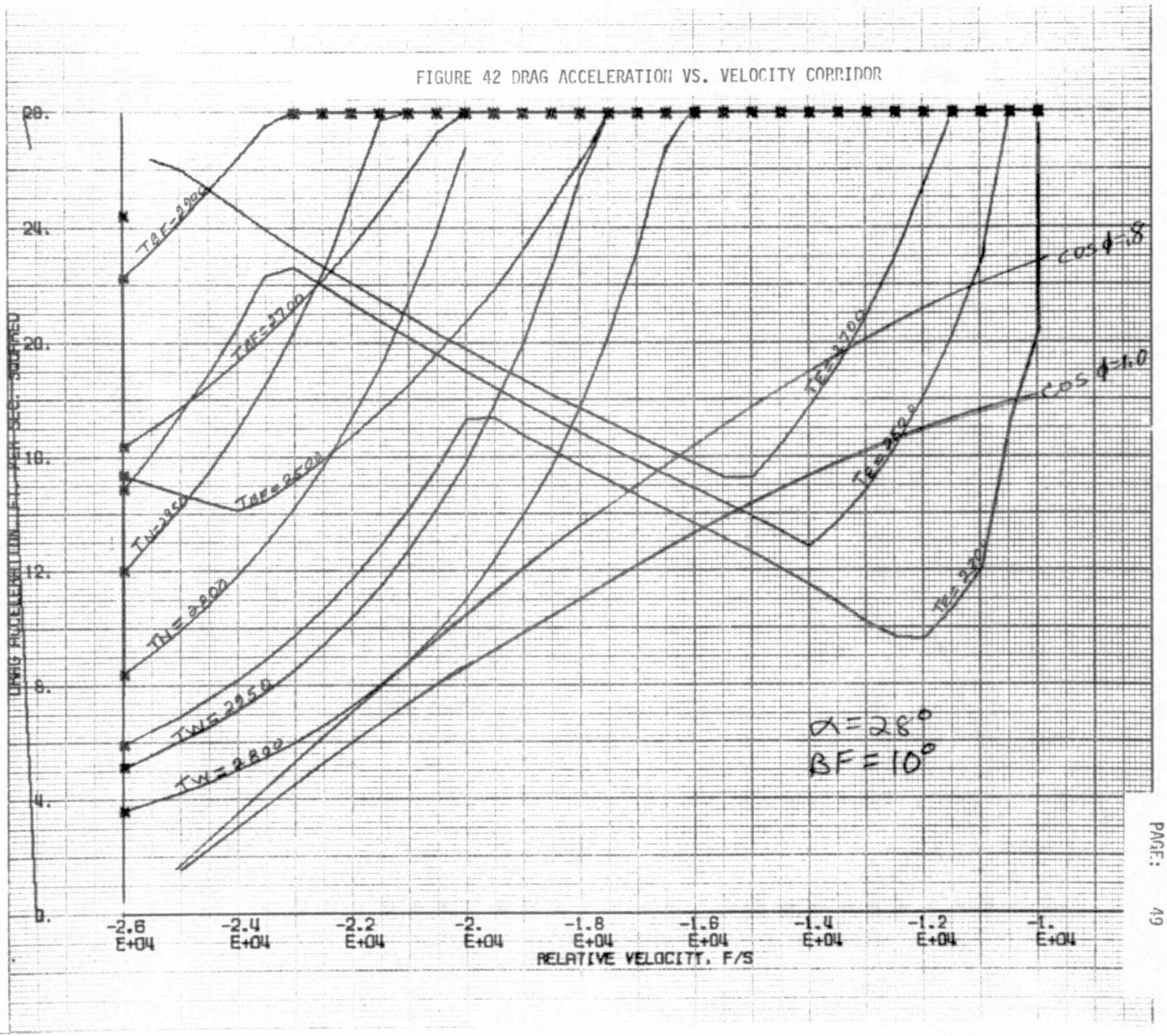

FIGURE 43 DRAG ACCELERATION VS. VELOCITY CORRIDOR

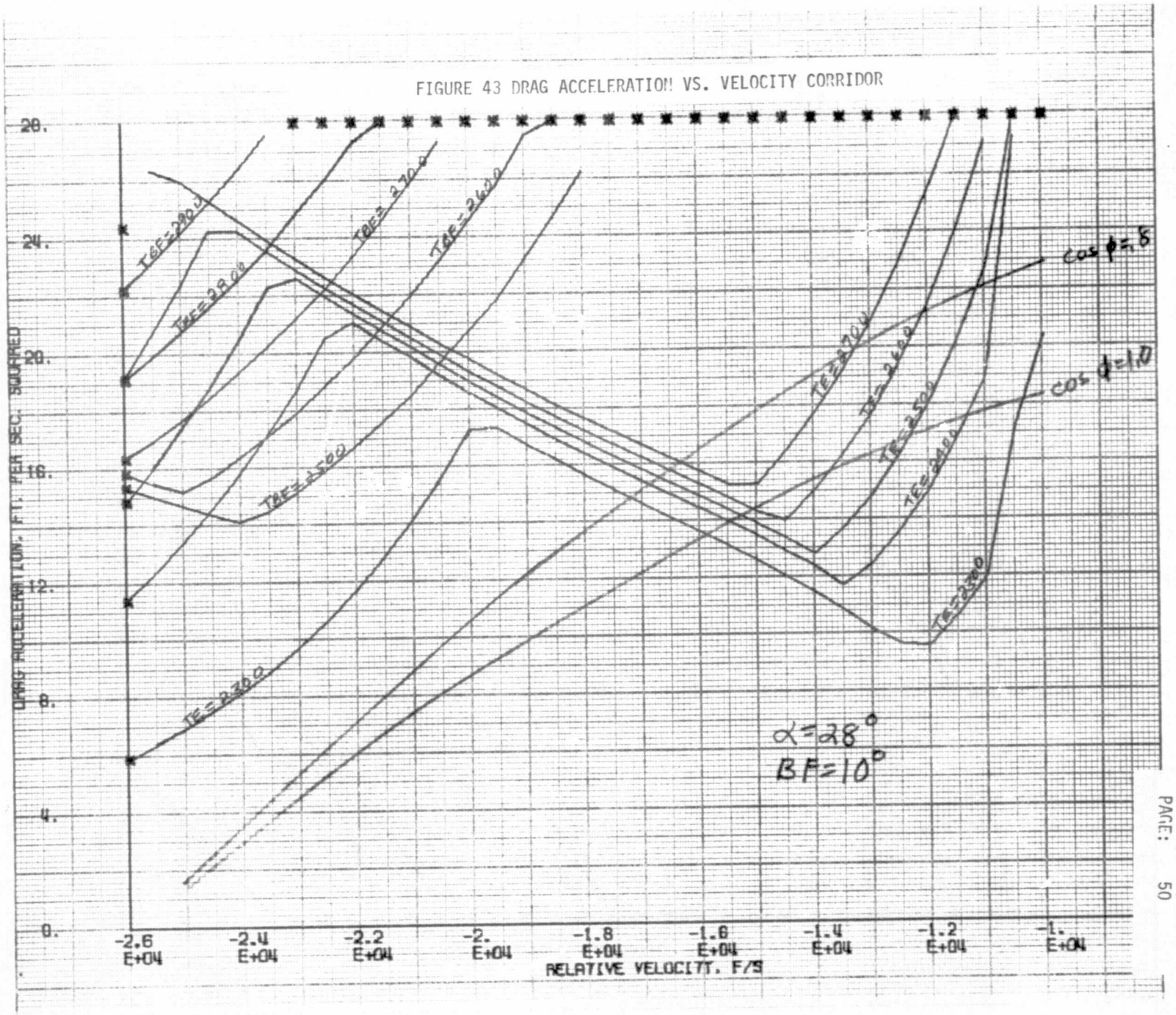

FIGURE 44 DRAG ACCELERATION VS. VELOCITY CORRIDOR

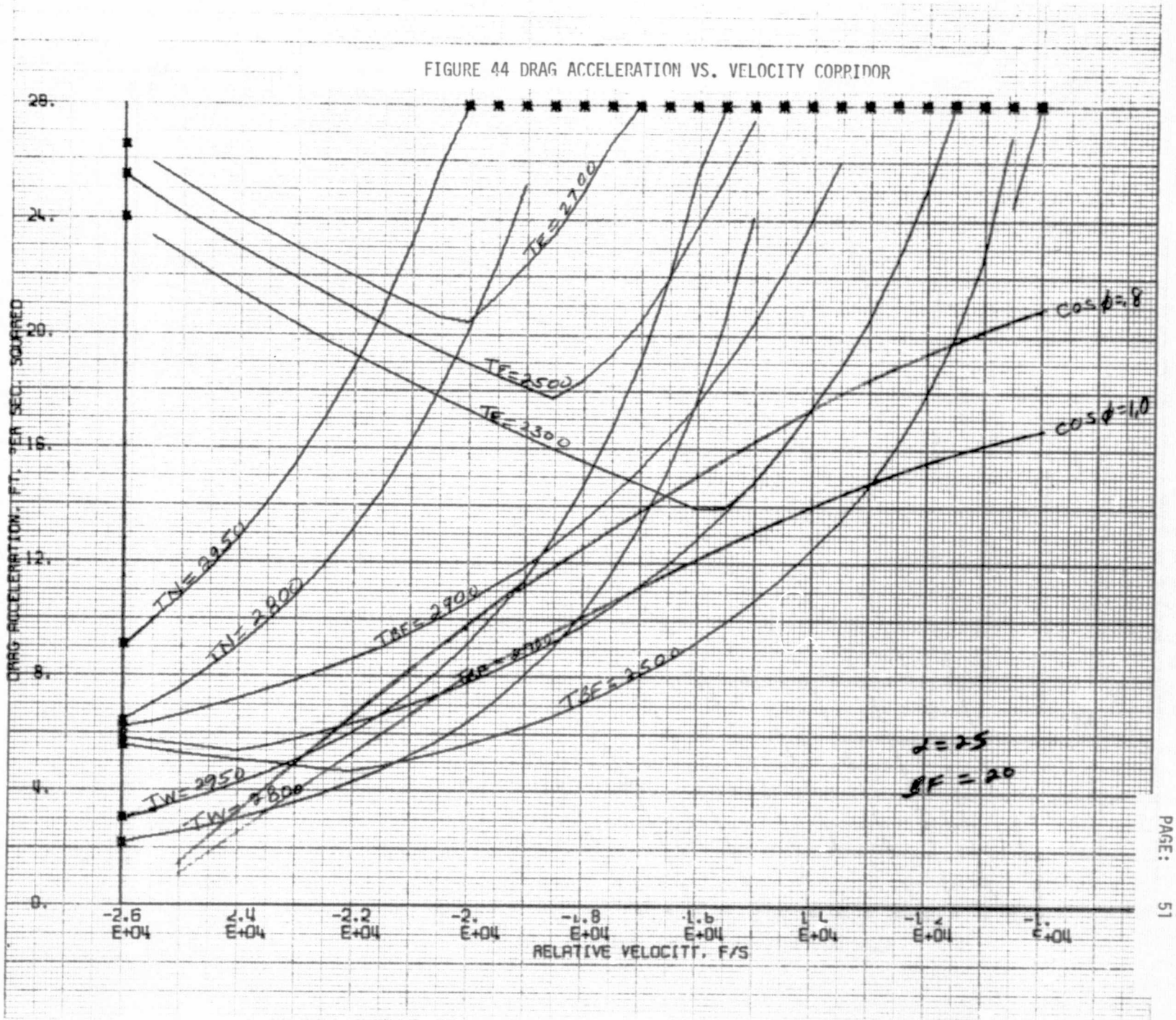

FIGURE 45 DRAG ACCELERATION VS. VELOCITY CORRIDOR

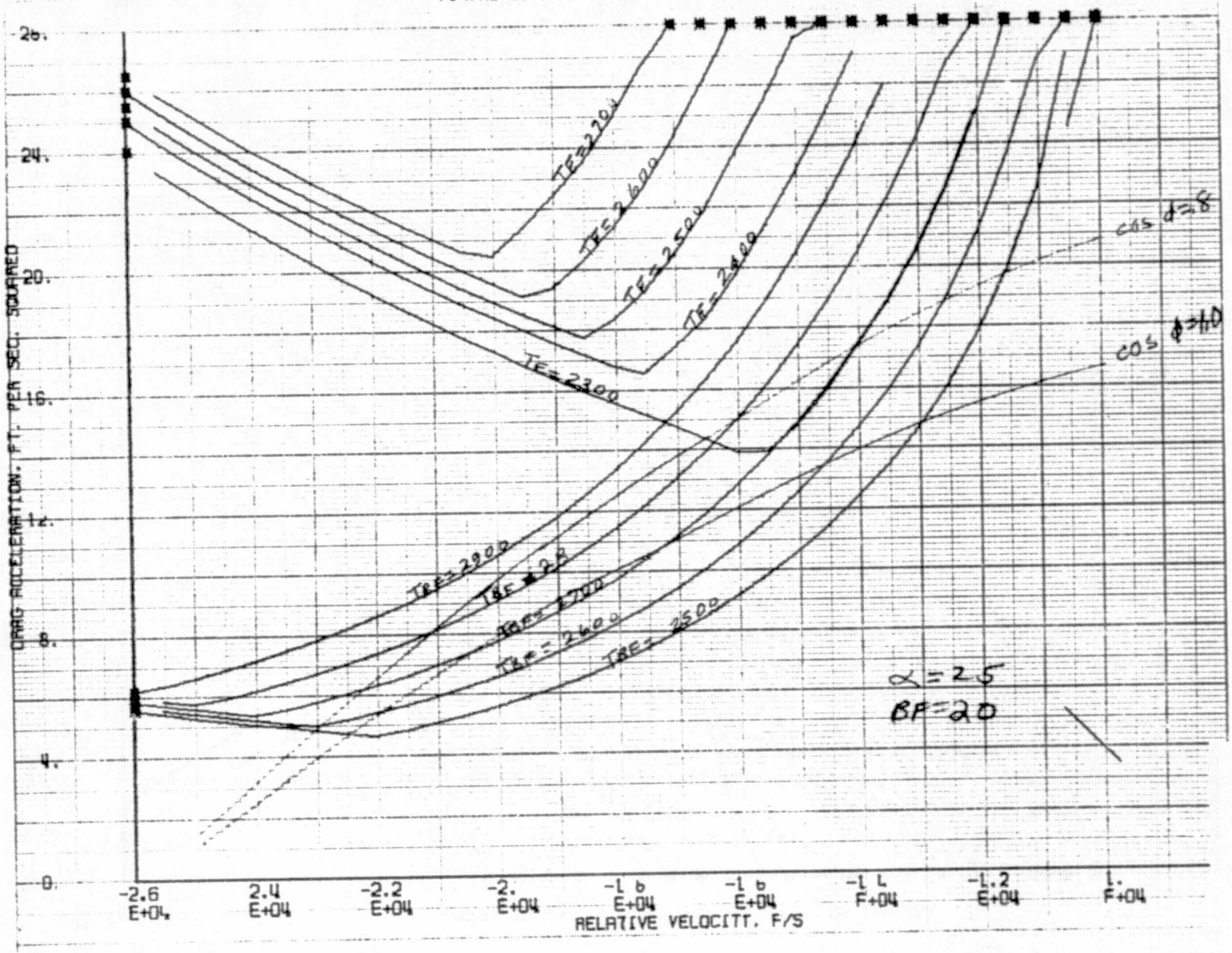

FIGURE 46 DRAG ACCELERATION VS. VELOCITY CORRIDOR

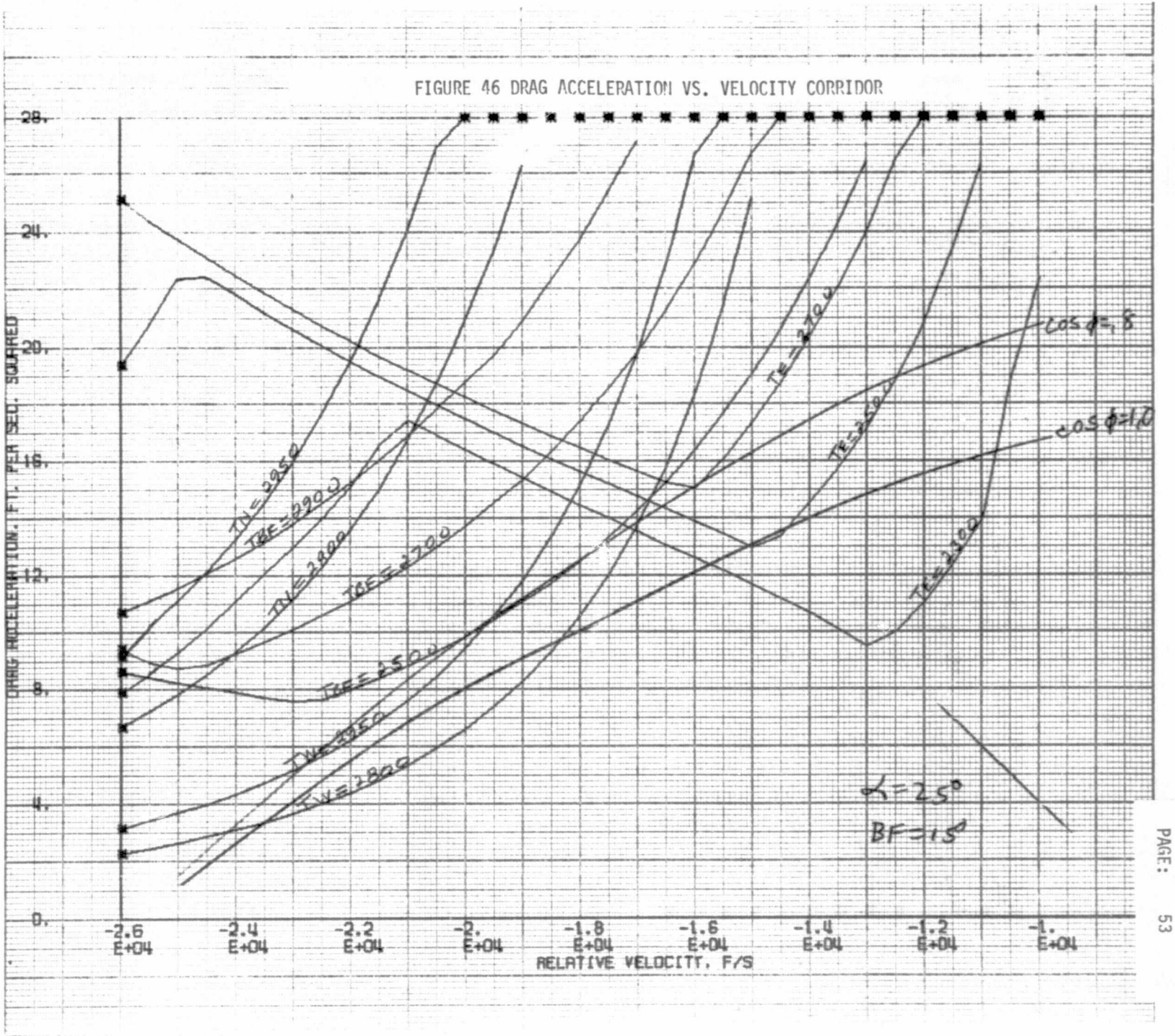

FIGURE 47 DRAG ACCELERATION VS. VELOCITY CORRIDOR

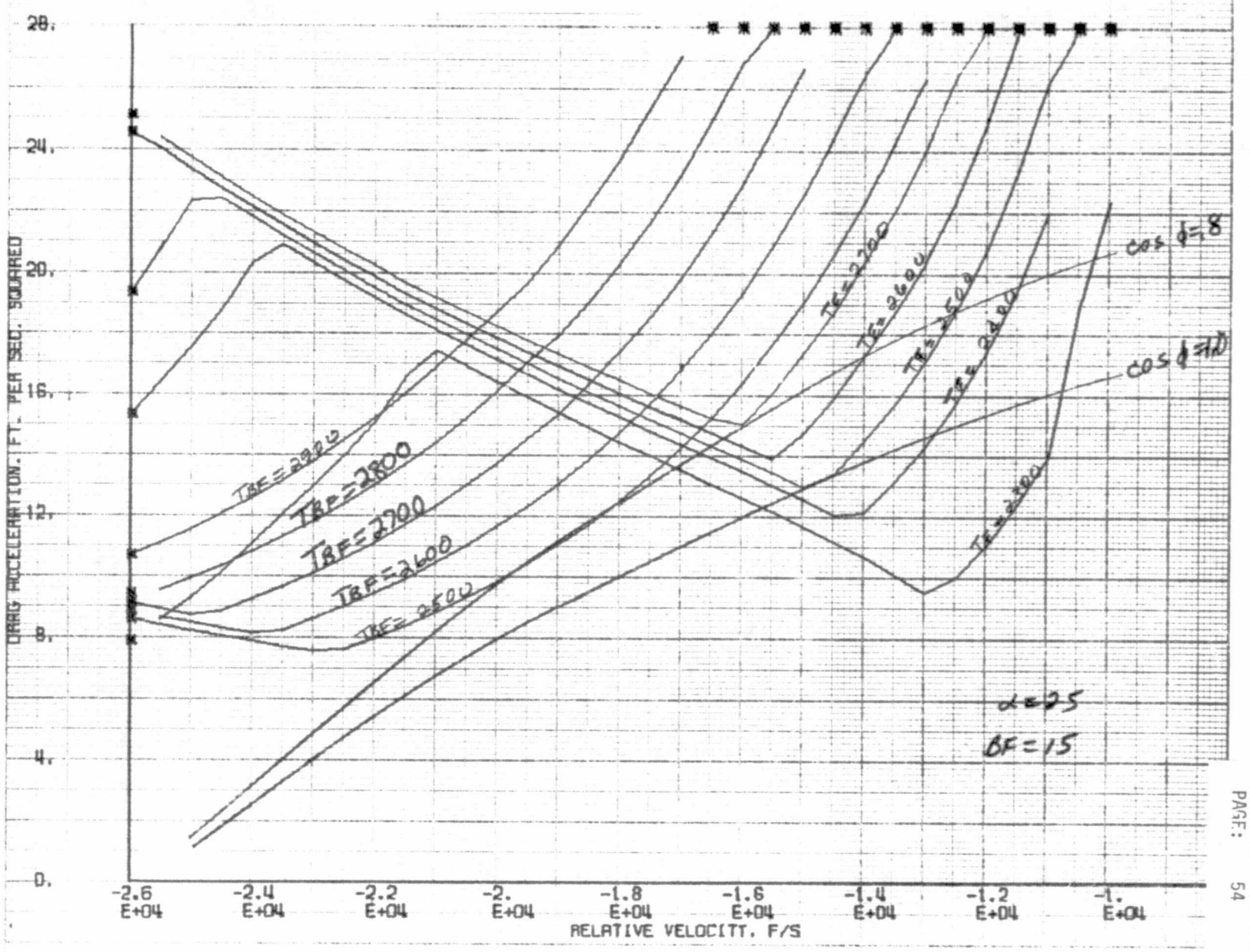

FIGURE 48 DRAG ACCELERATION VS. VELOCITY CORRIDOR

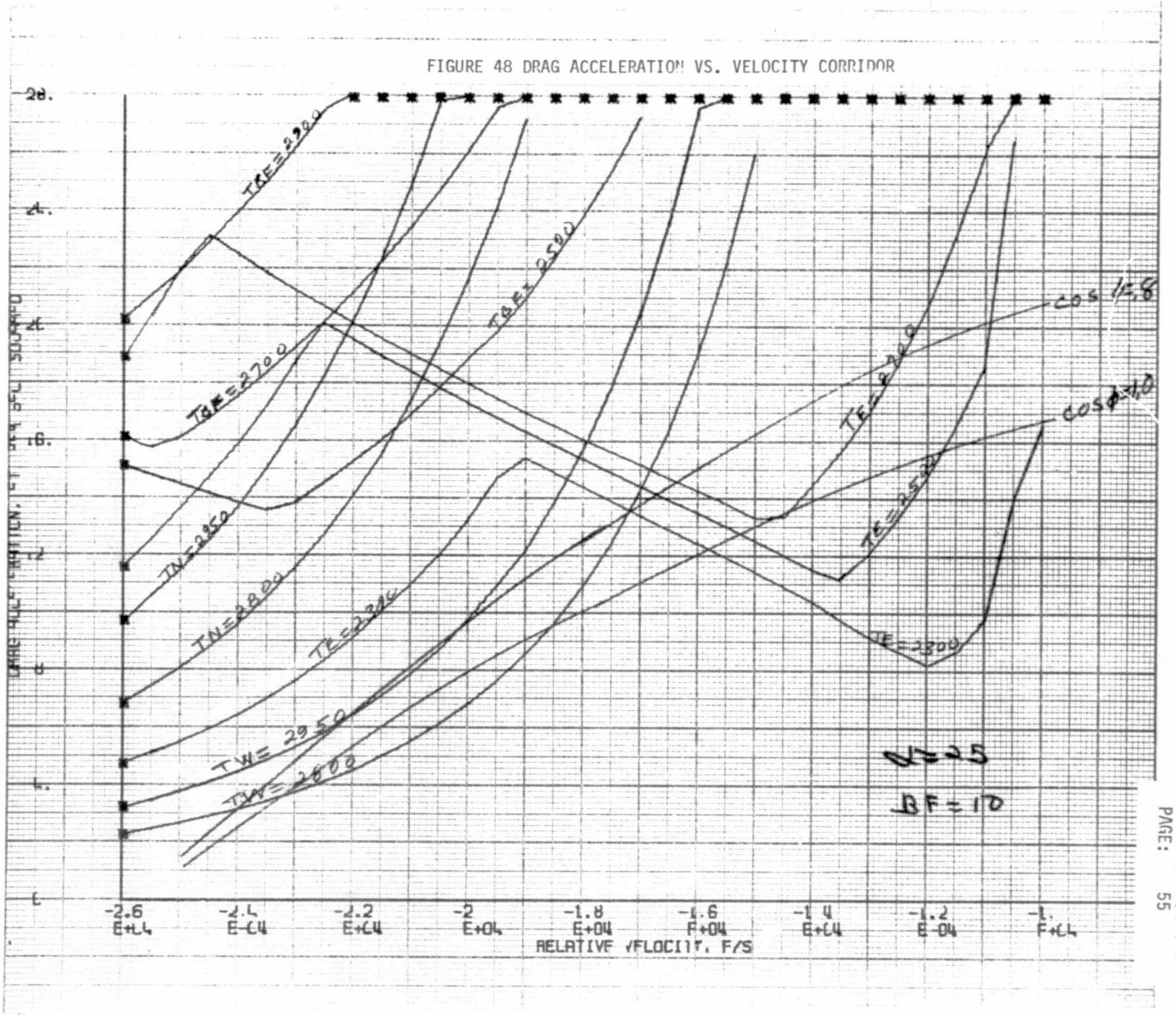

FIGURE 49 DRAG ACCELERATION VS. VELOCITY CORRIDOR

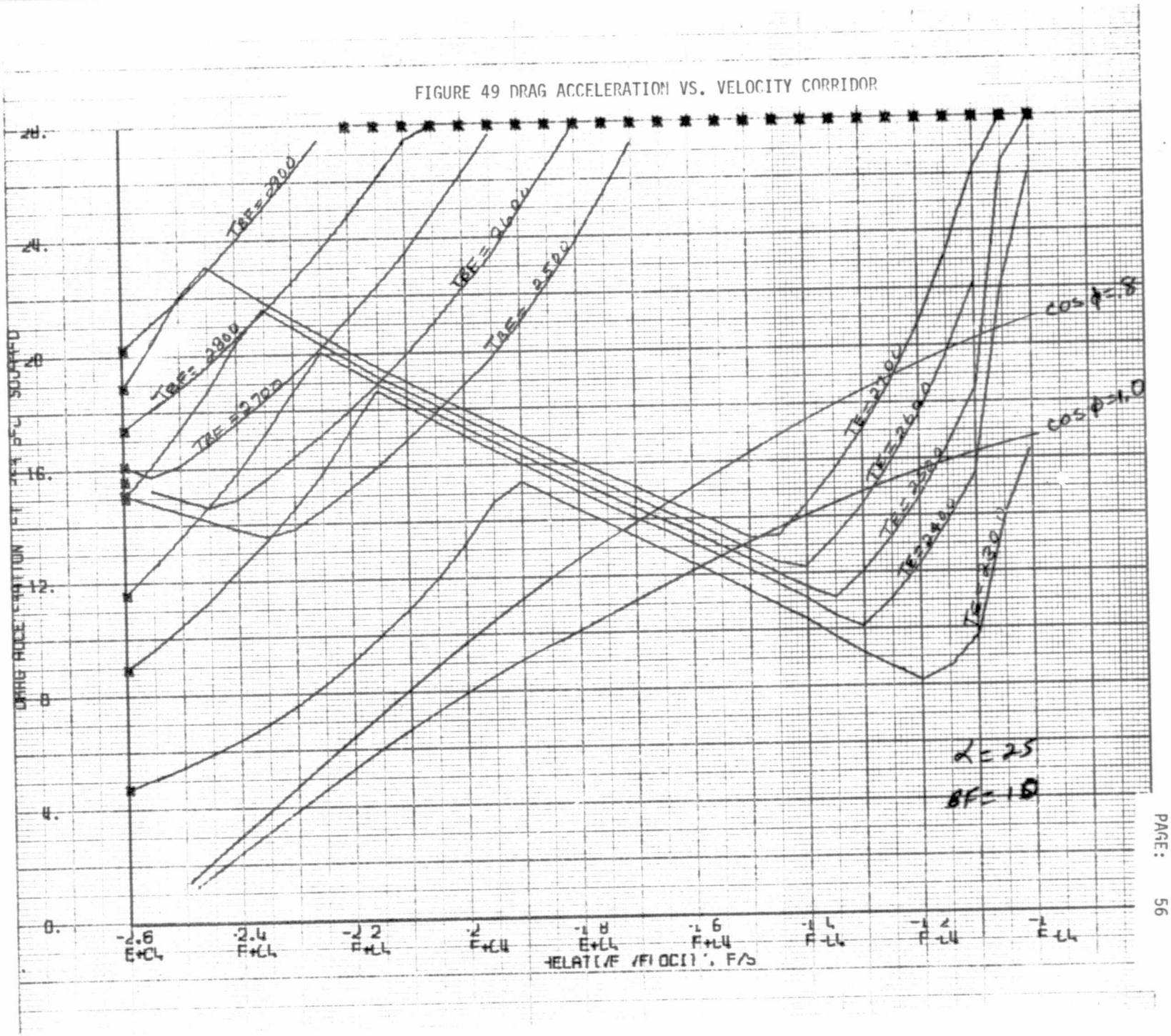

FIGURE 50 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

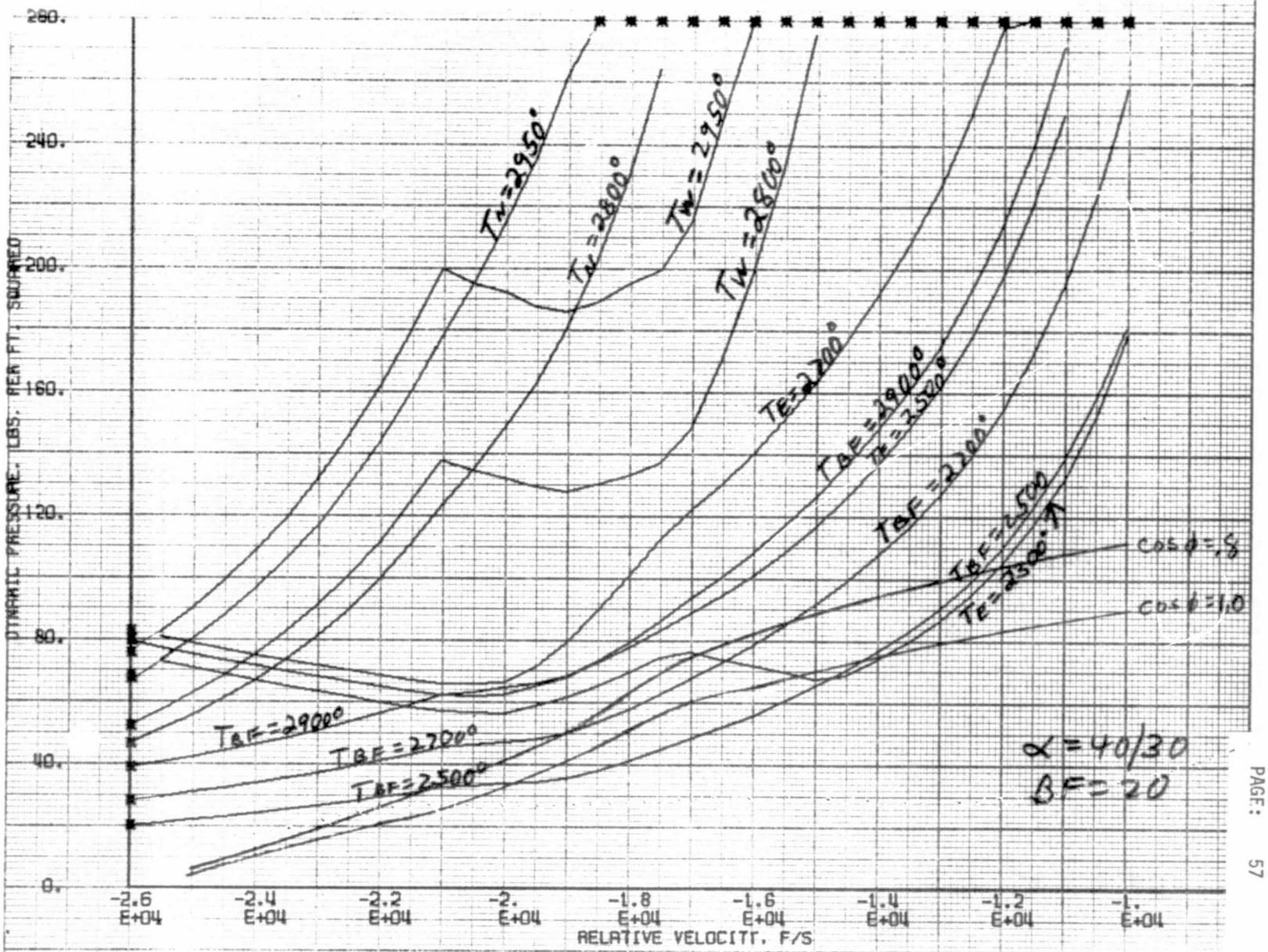

FIGURE 51 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

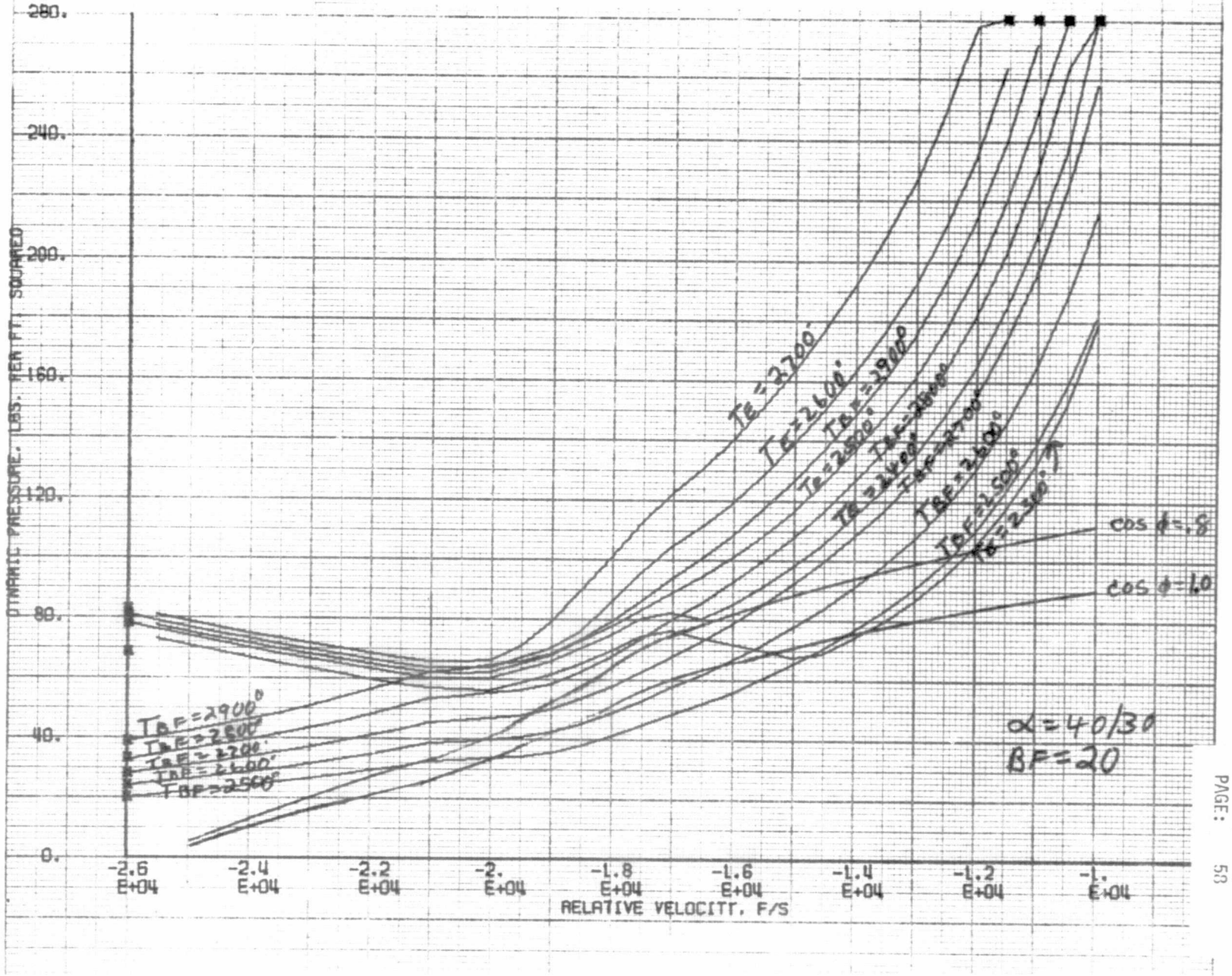

FIGURE 52 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

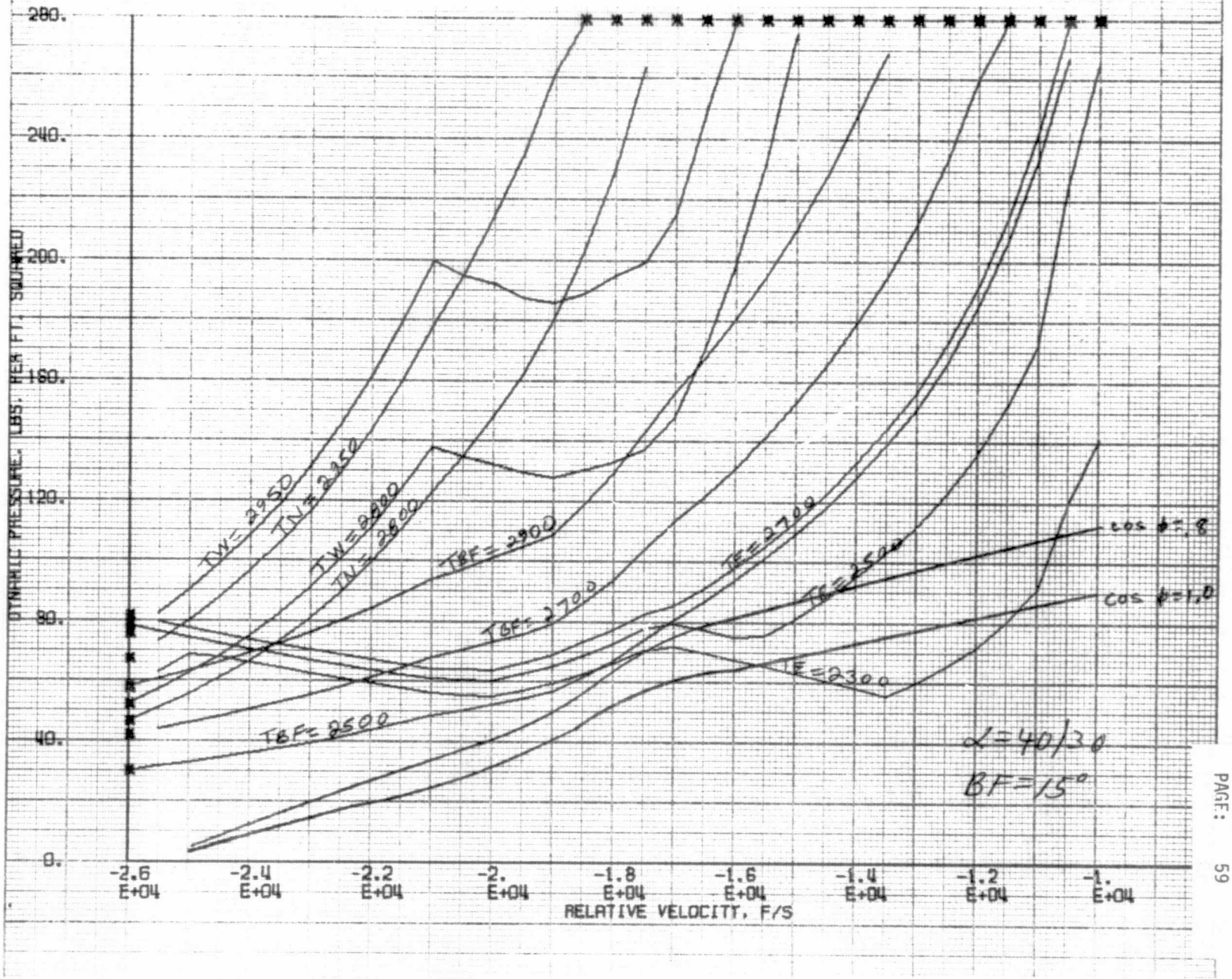

FIGURE 53 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

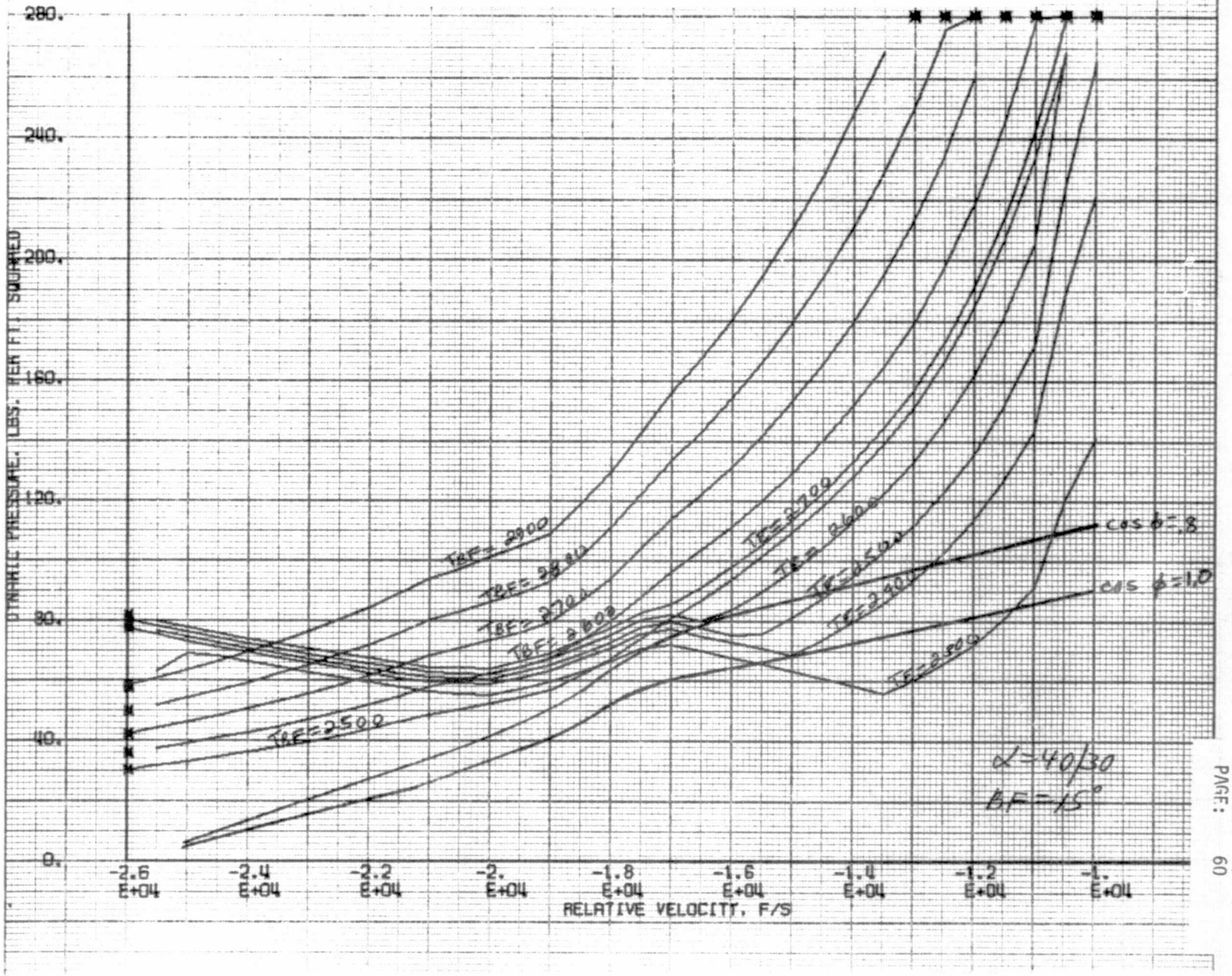

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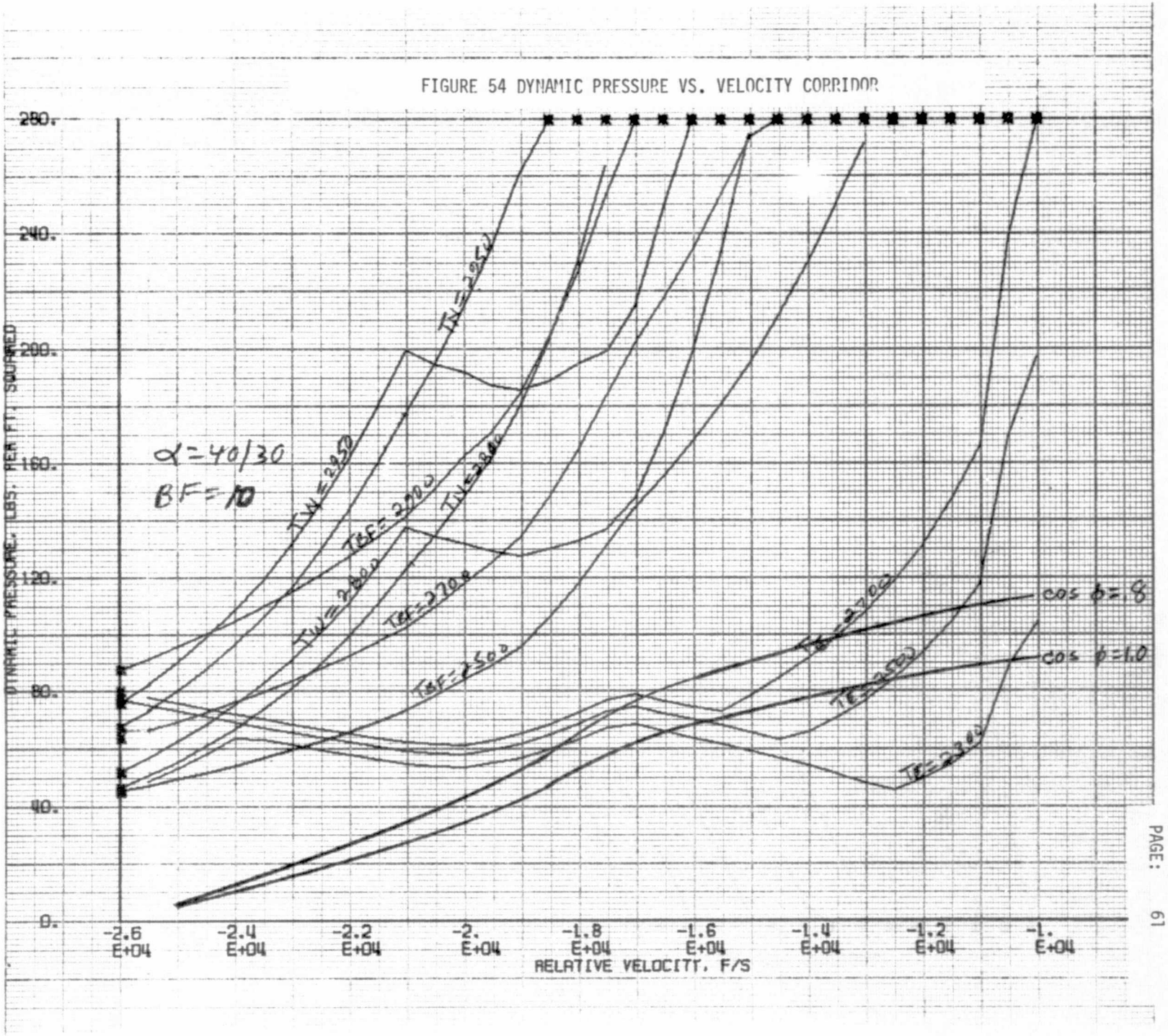
FIGURE 54 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR



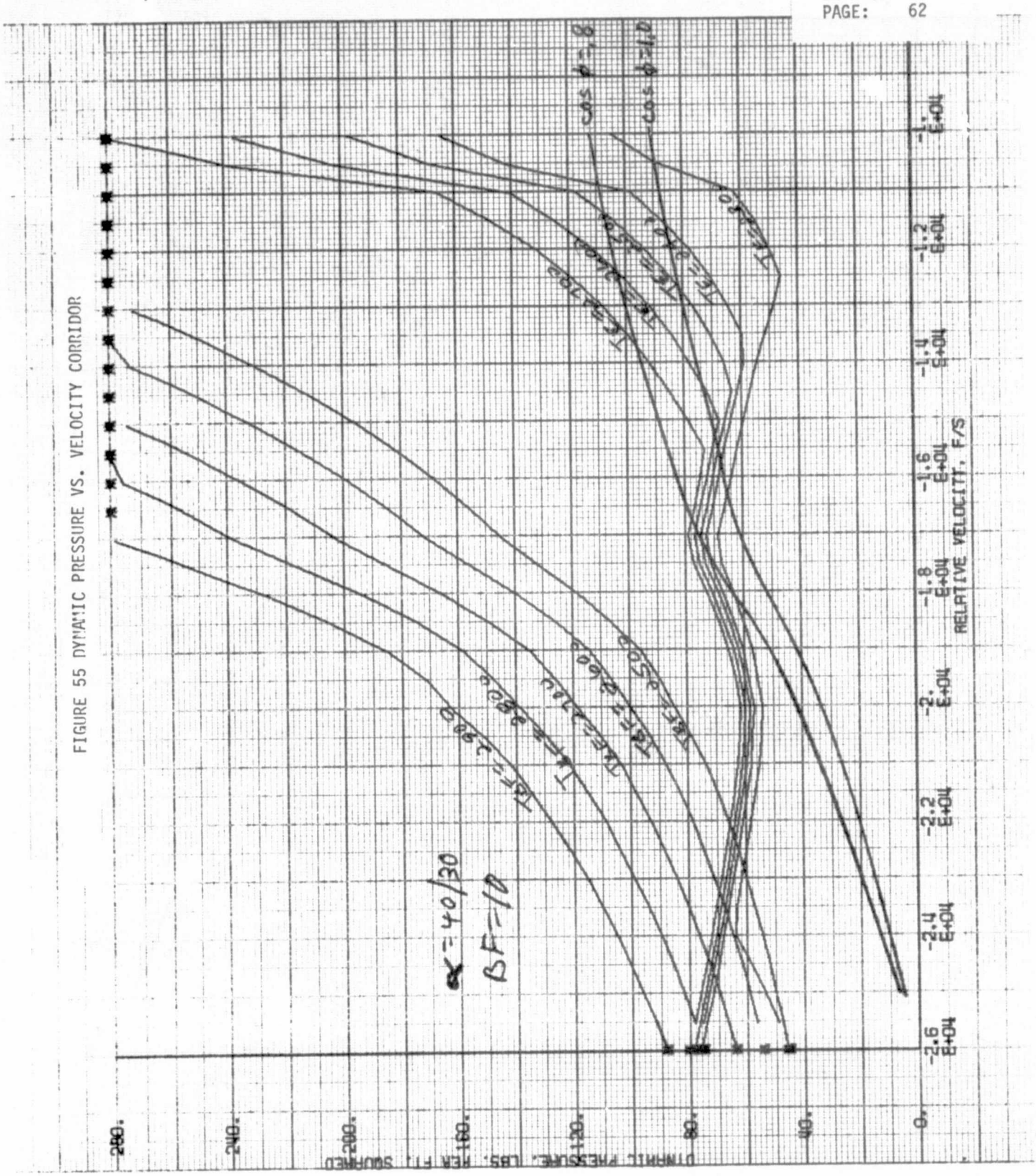


FIGURE 56 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

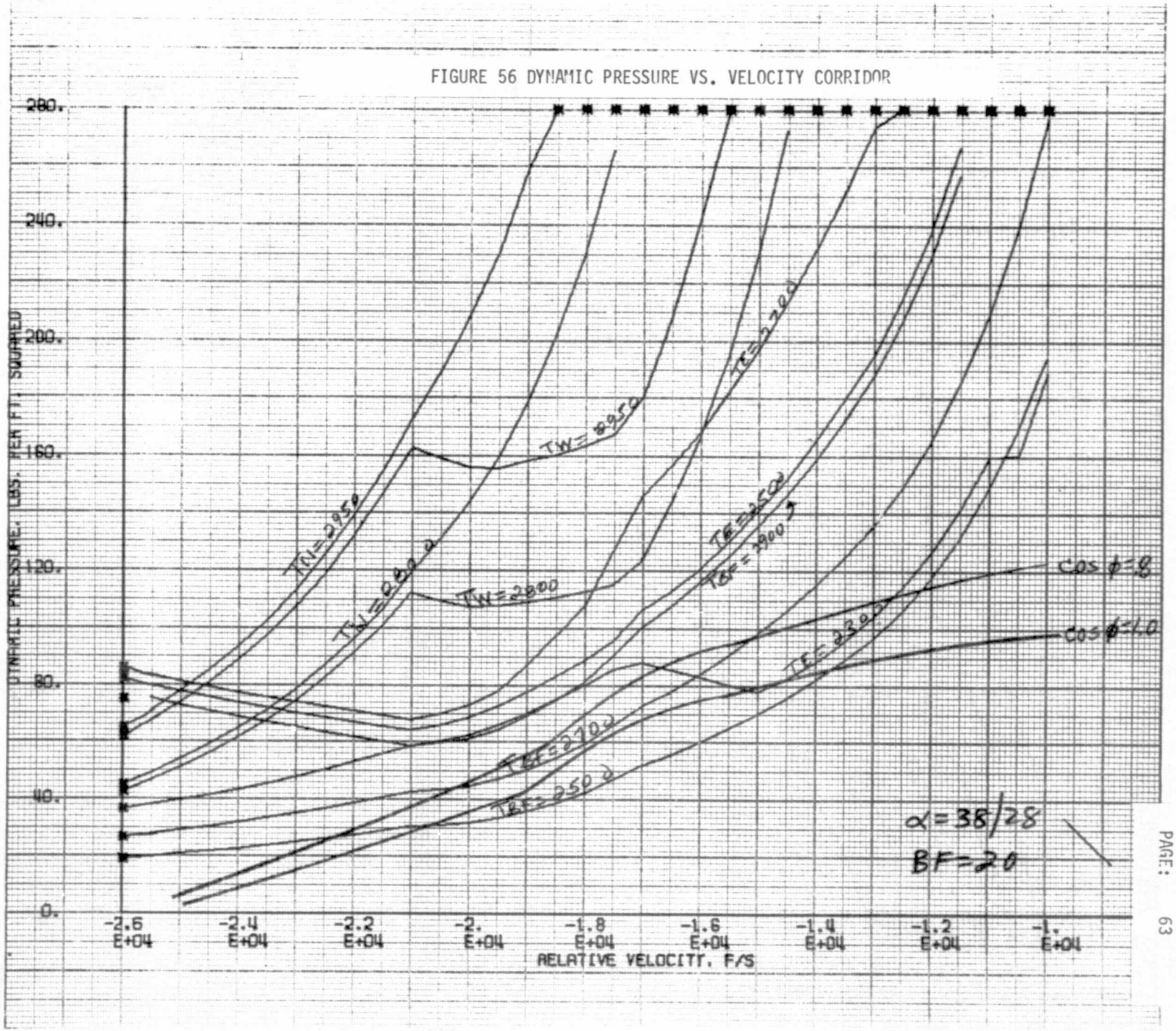


FIGURE 57 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

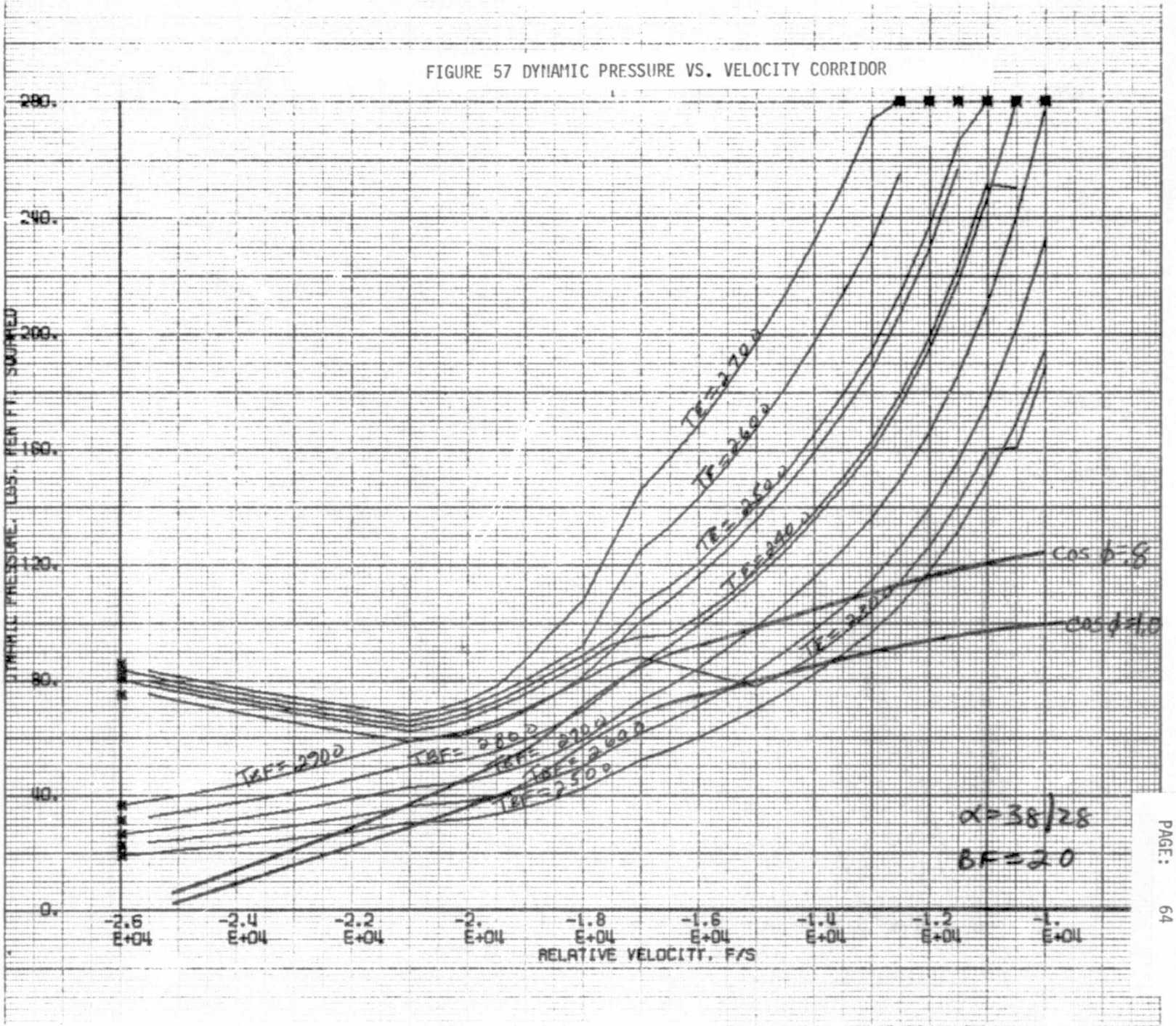


FIGURE 58 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

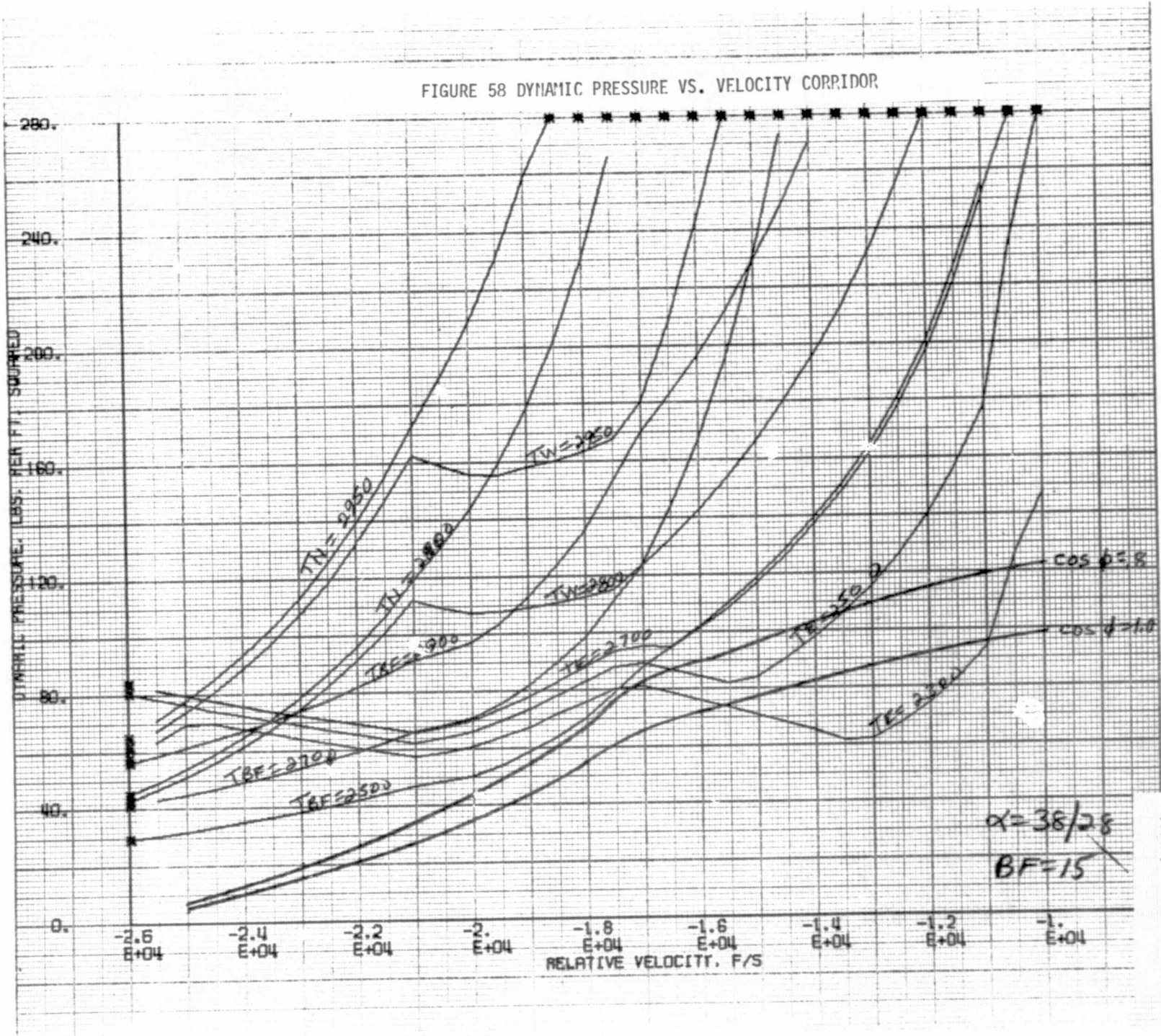


FIGURE 59 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

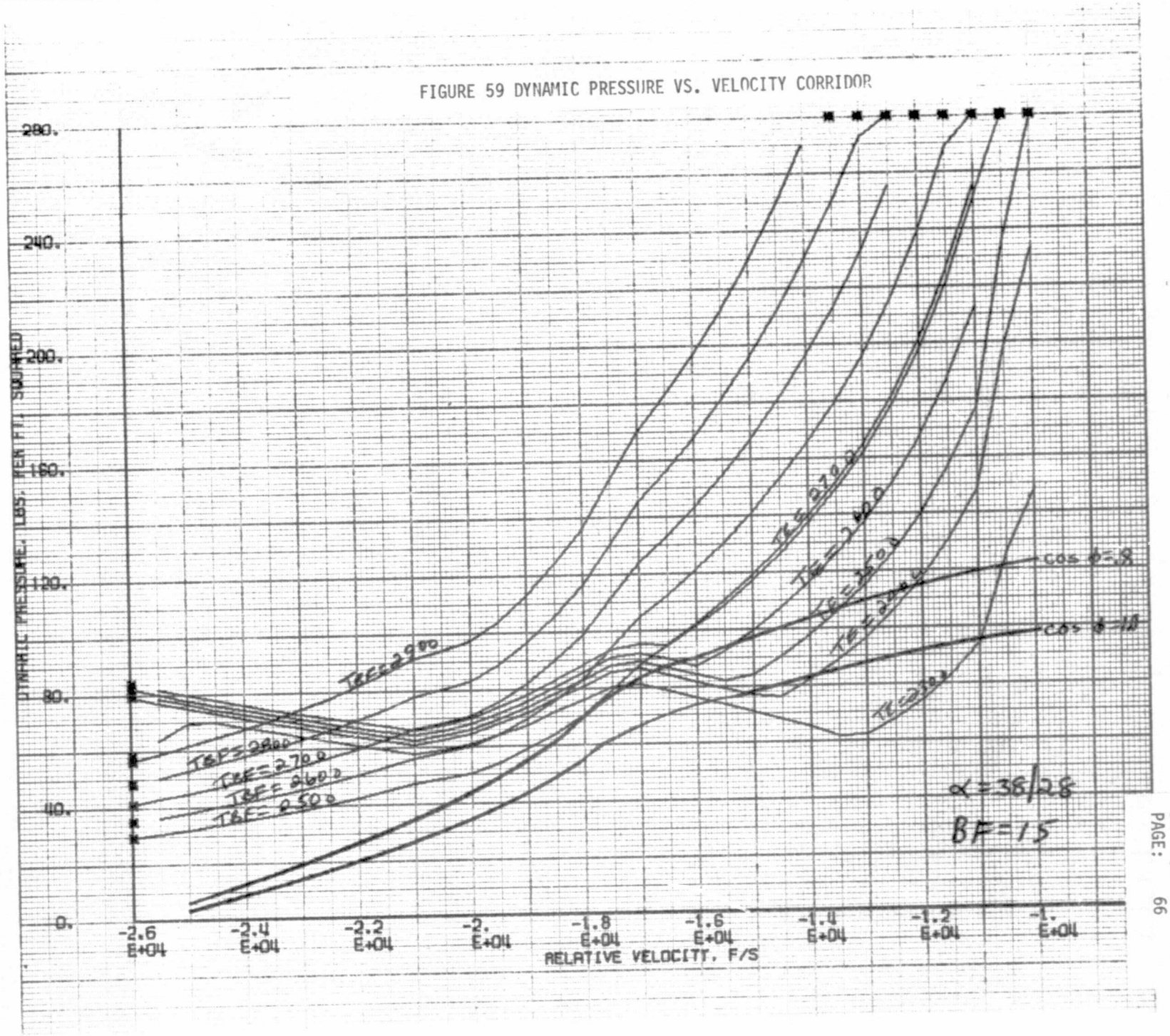


FIGURE 60 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

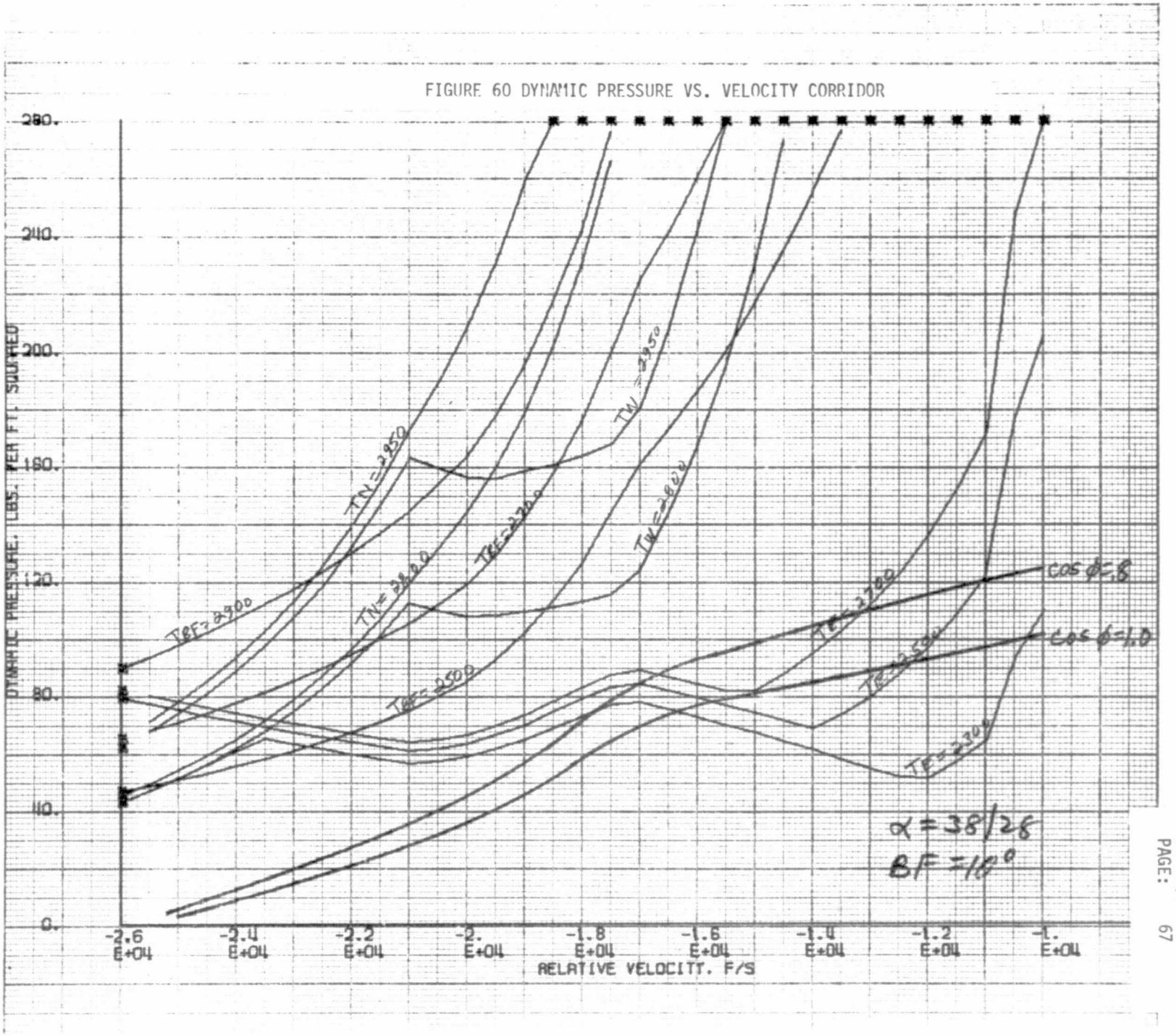


FIGURE 61 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

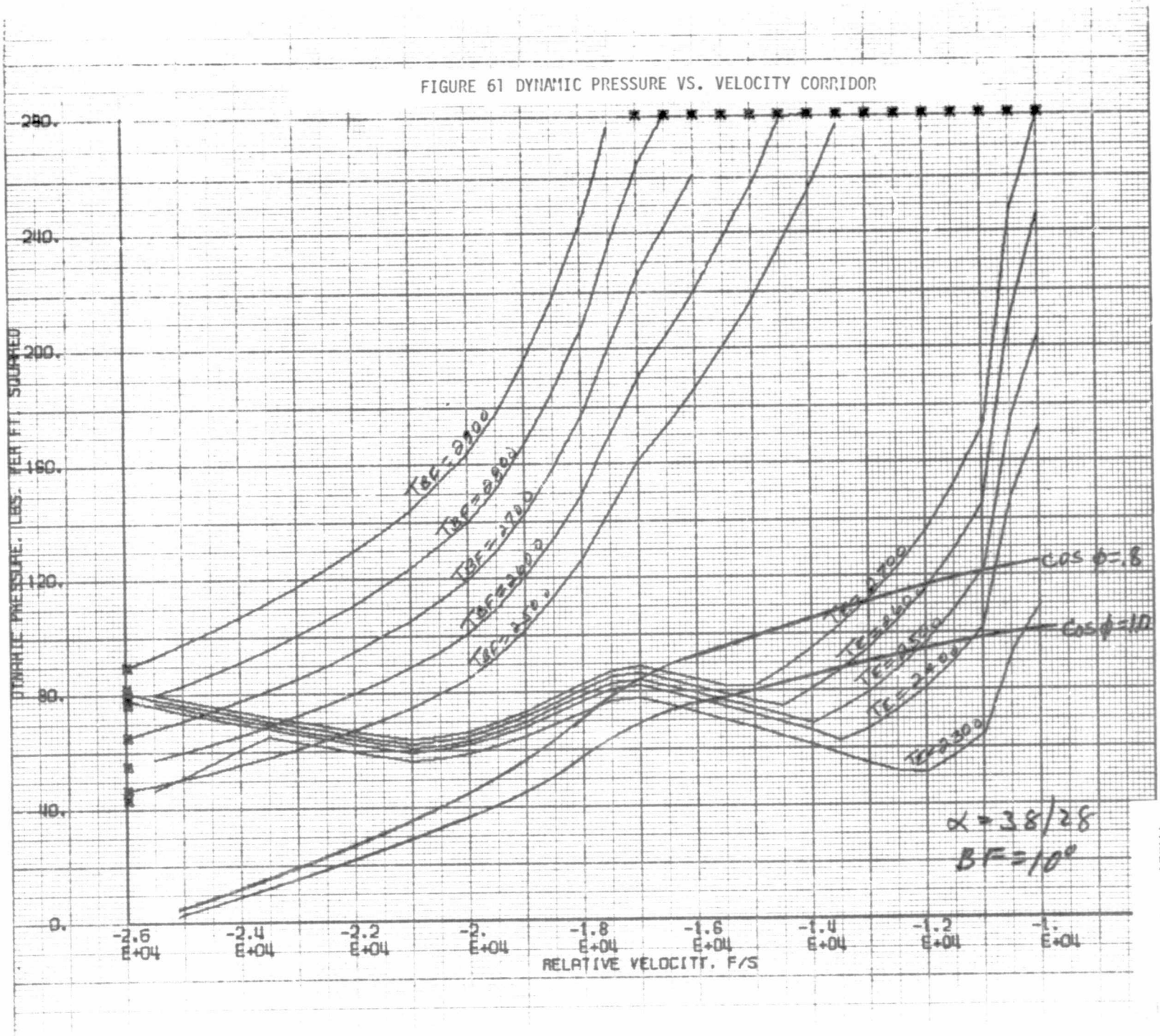


FIGURE 62 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

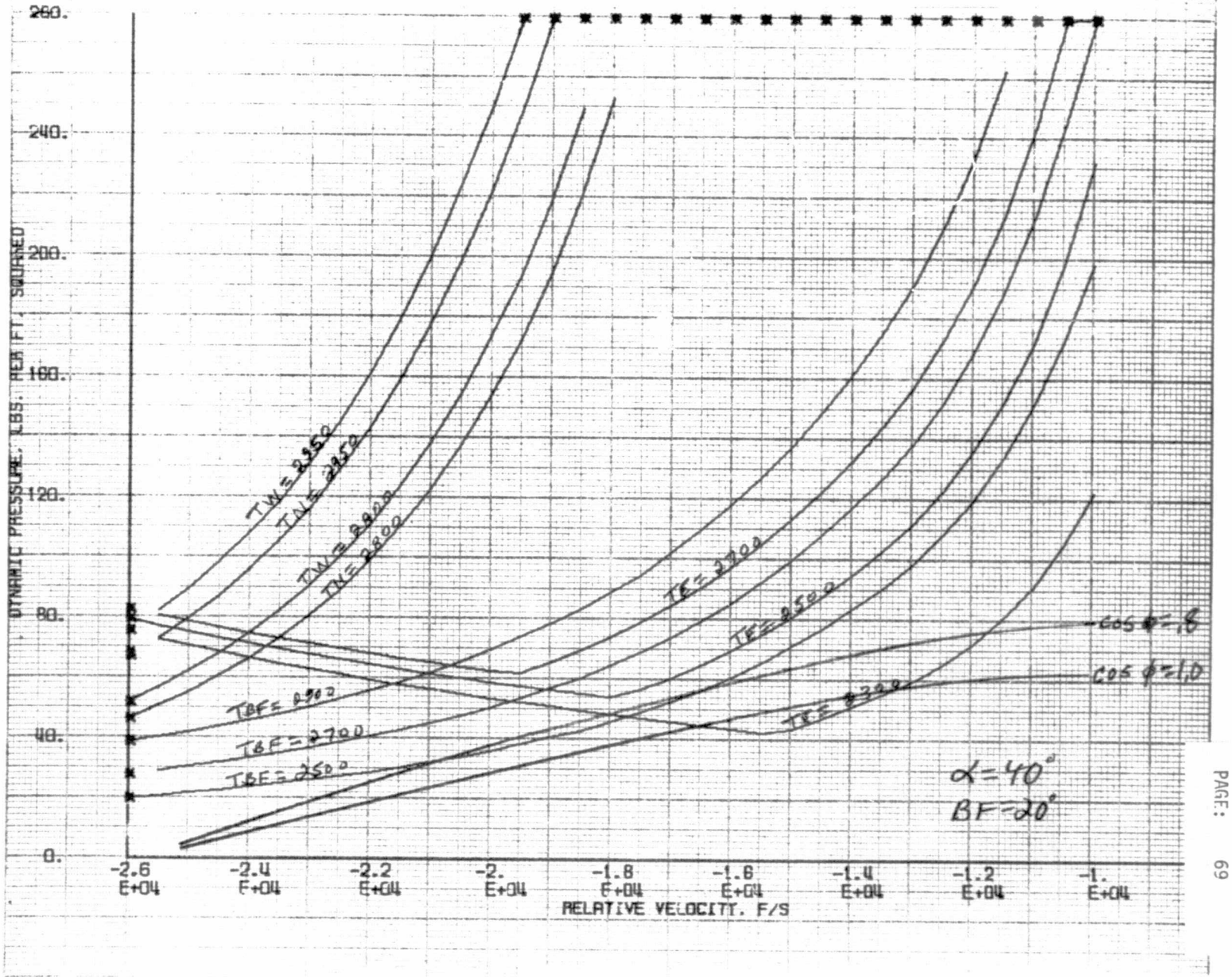


FIGURE 63 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

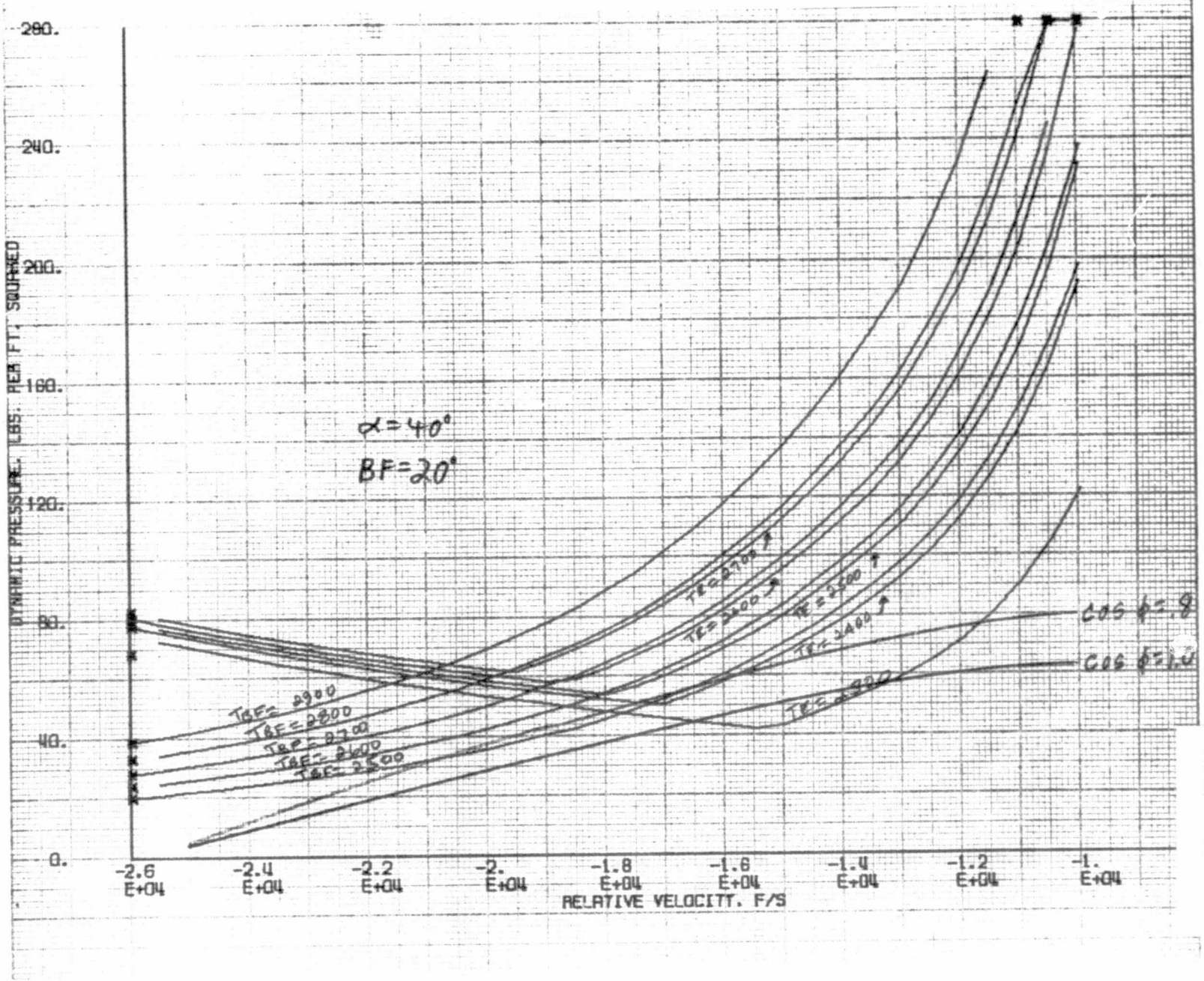


FIGURE 64 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

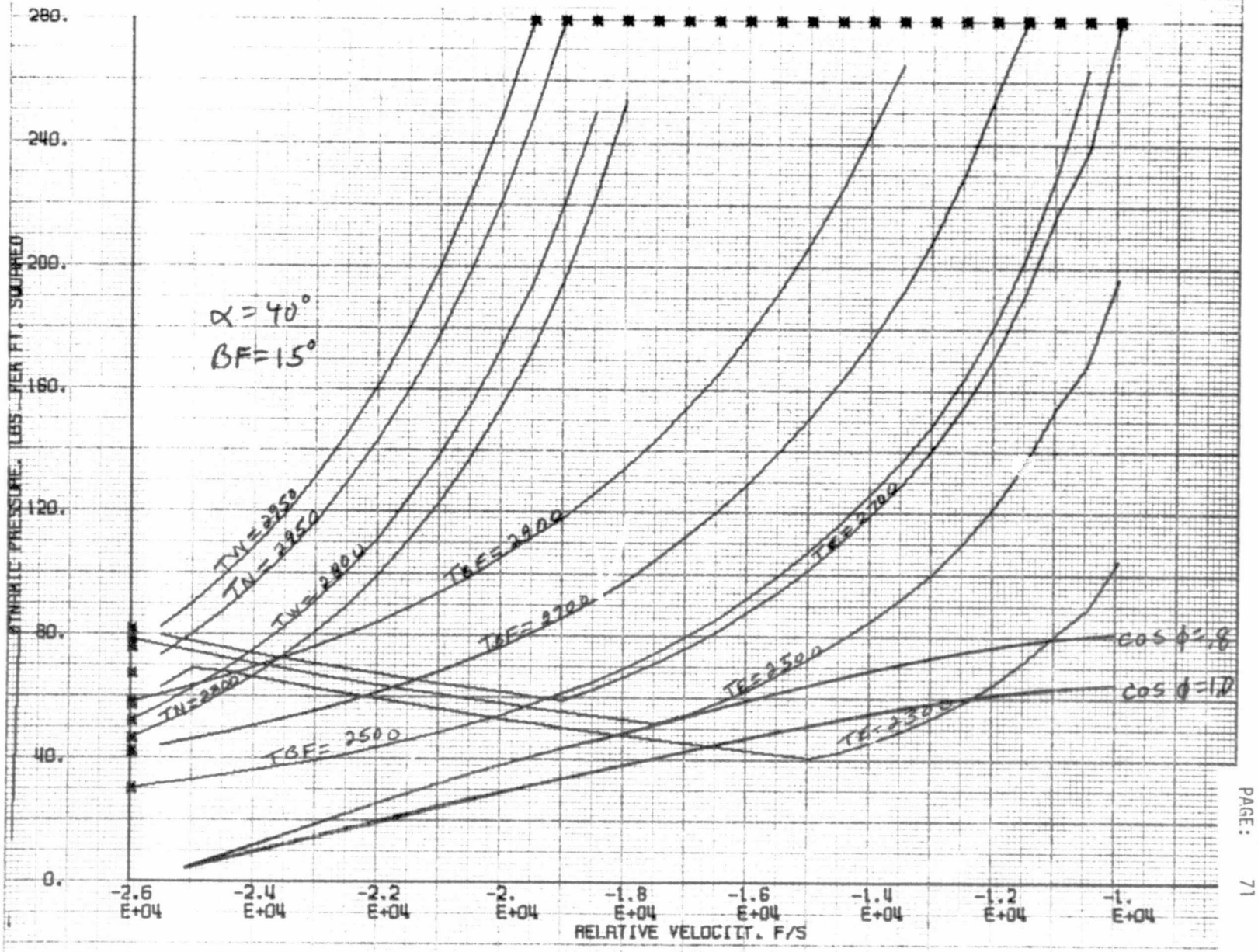


FIGURE 65 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

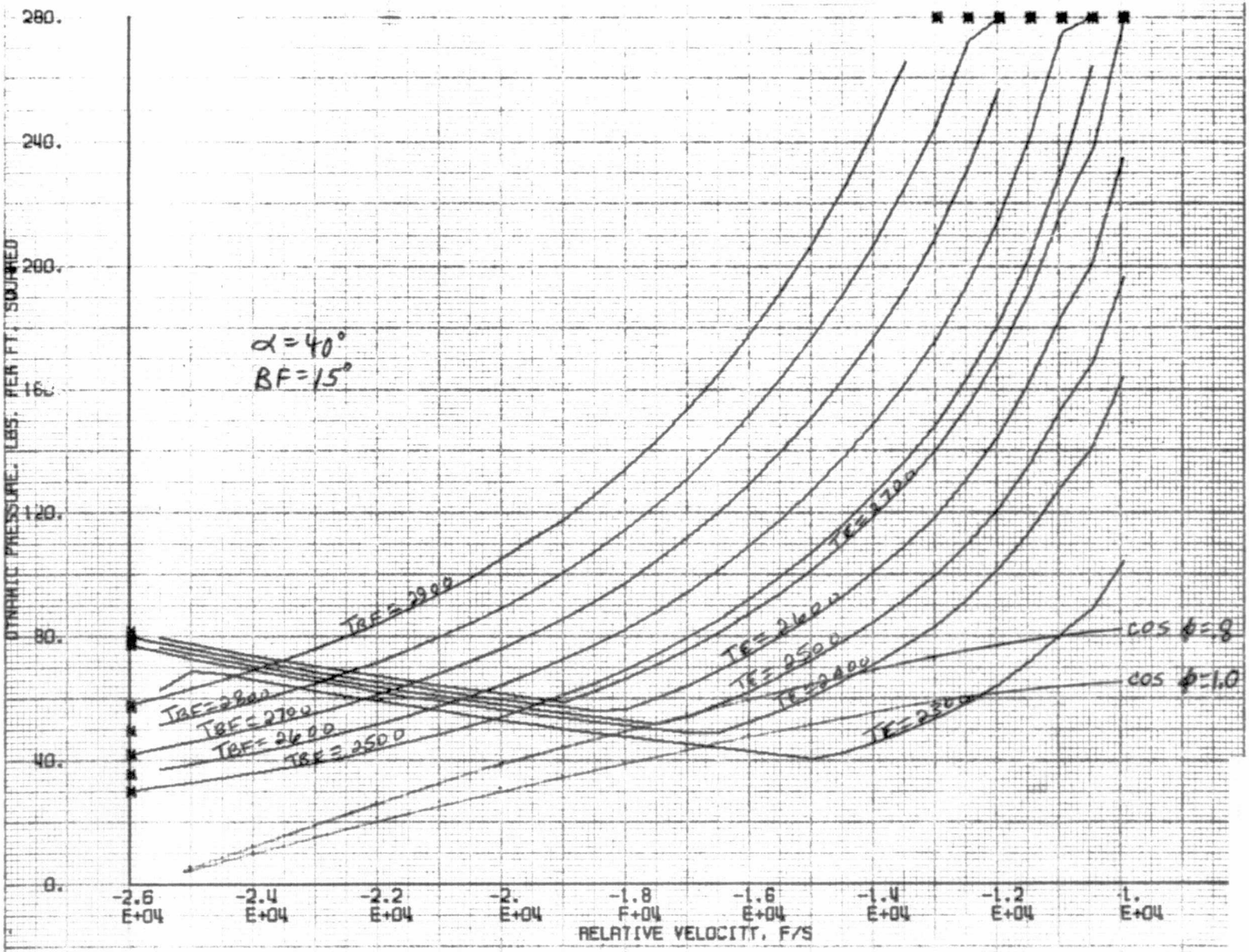


FIGURE 66 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

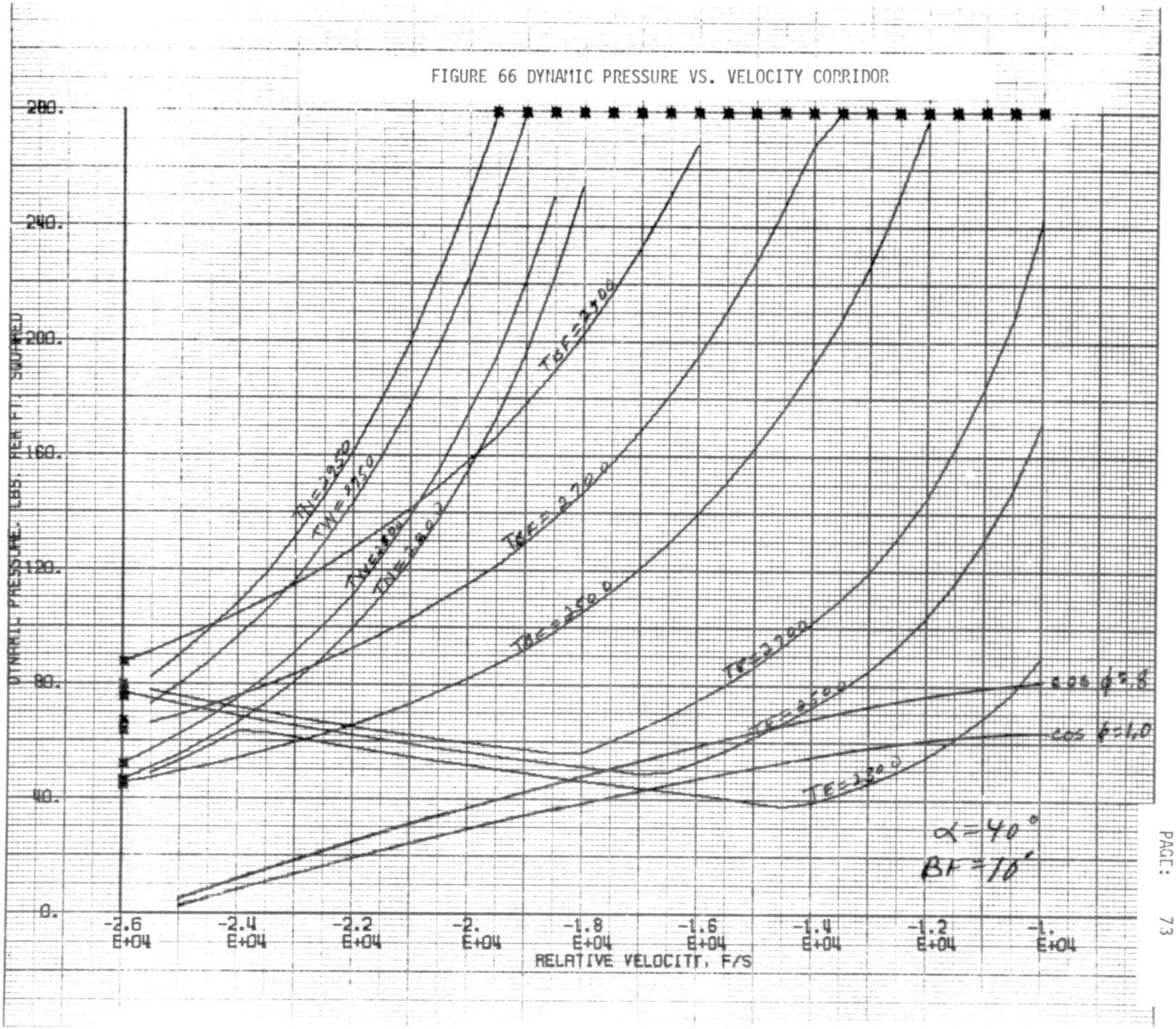


FIGURE 67 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

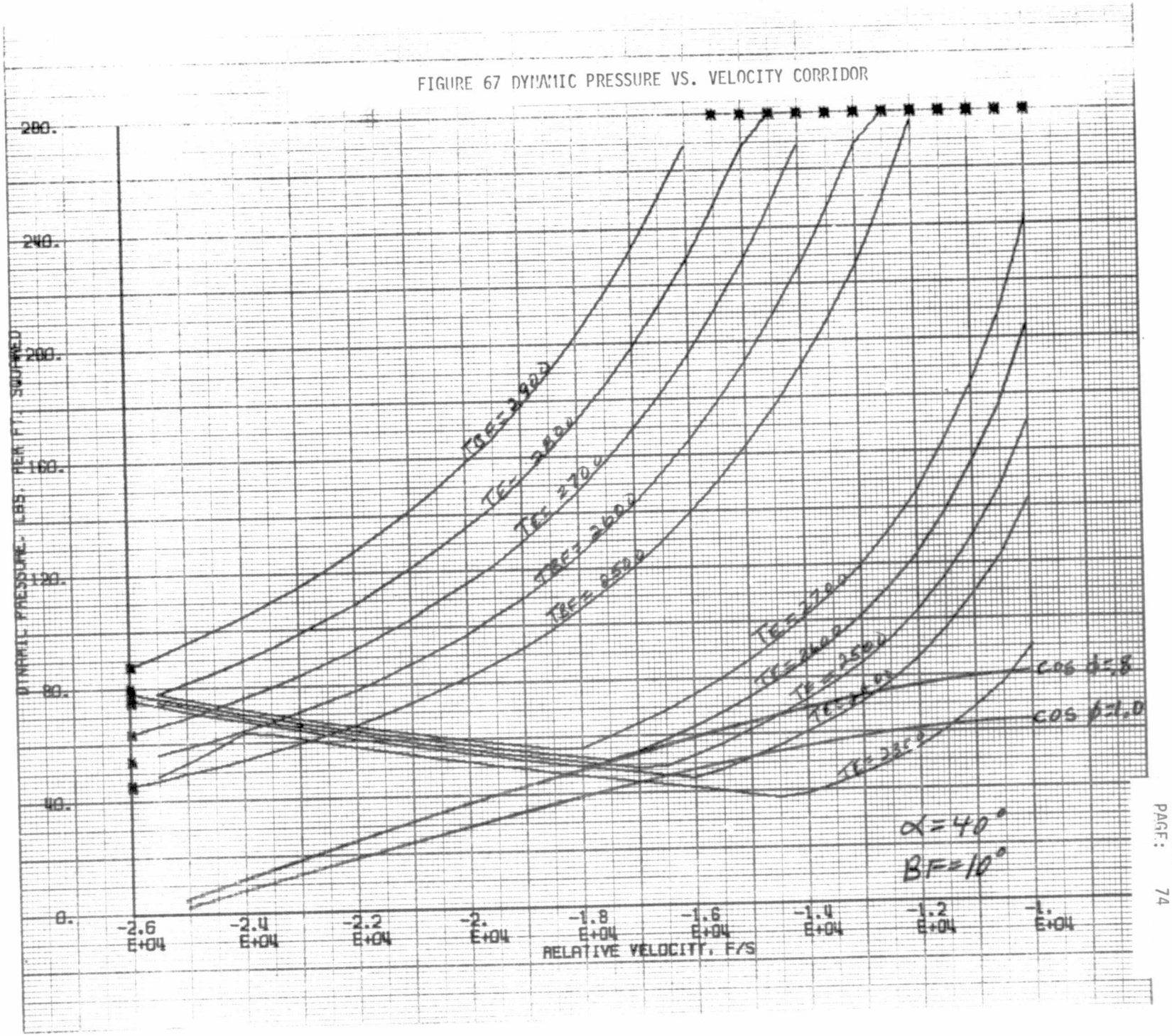


FIGURE 68 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

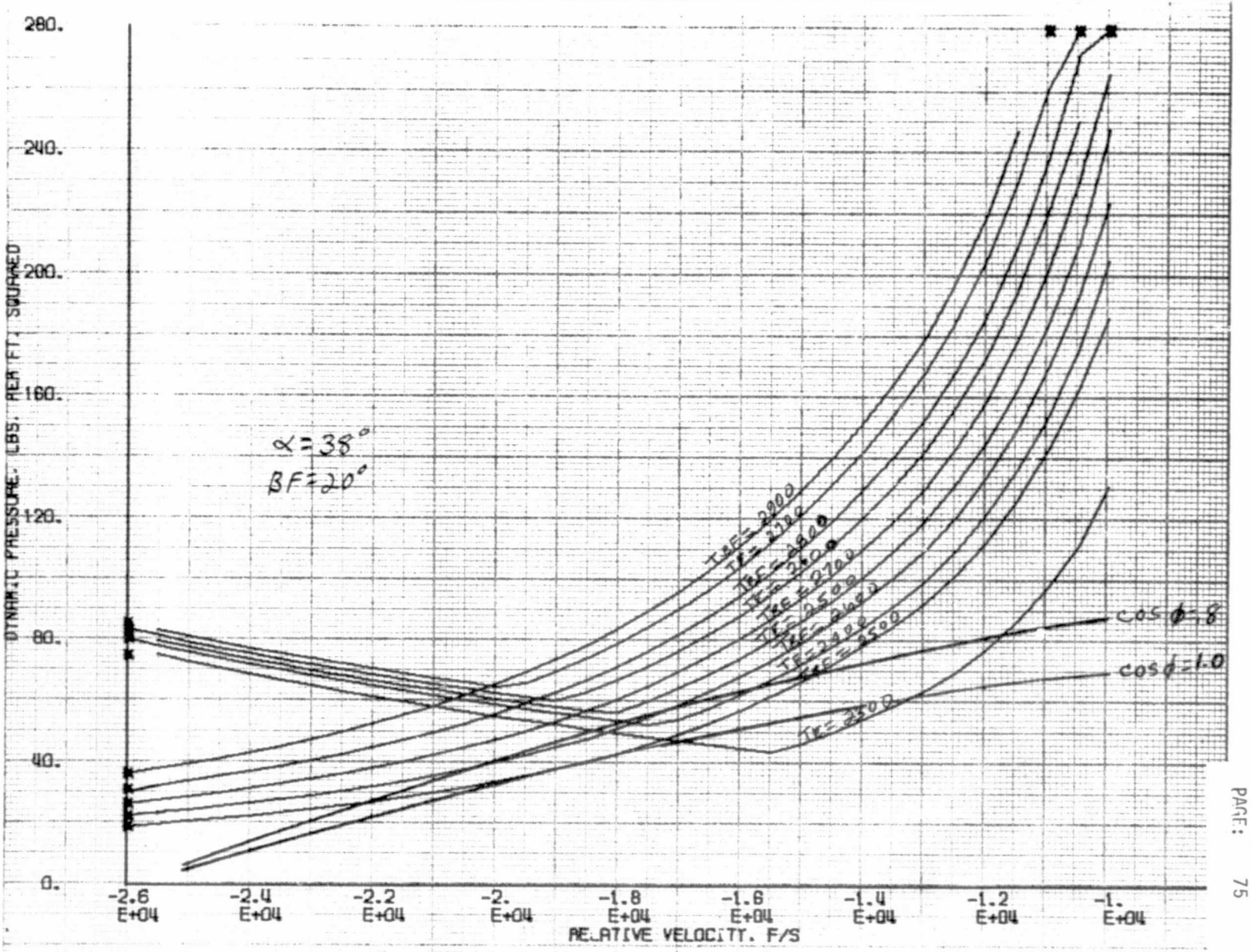


FIGURE 69 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

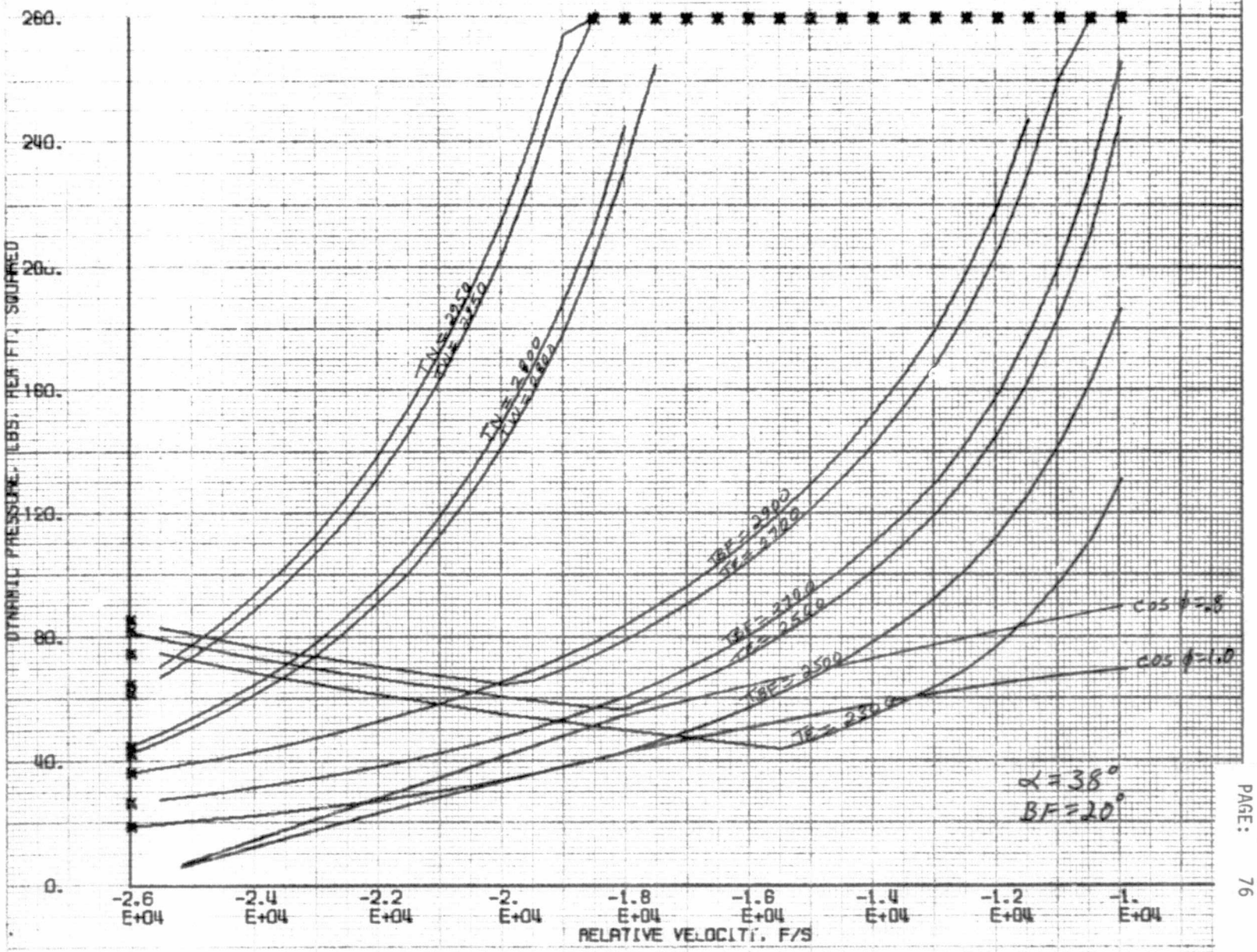


FIGURE 70 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

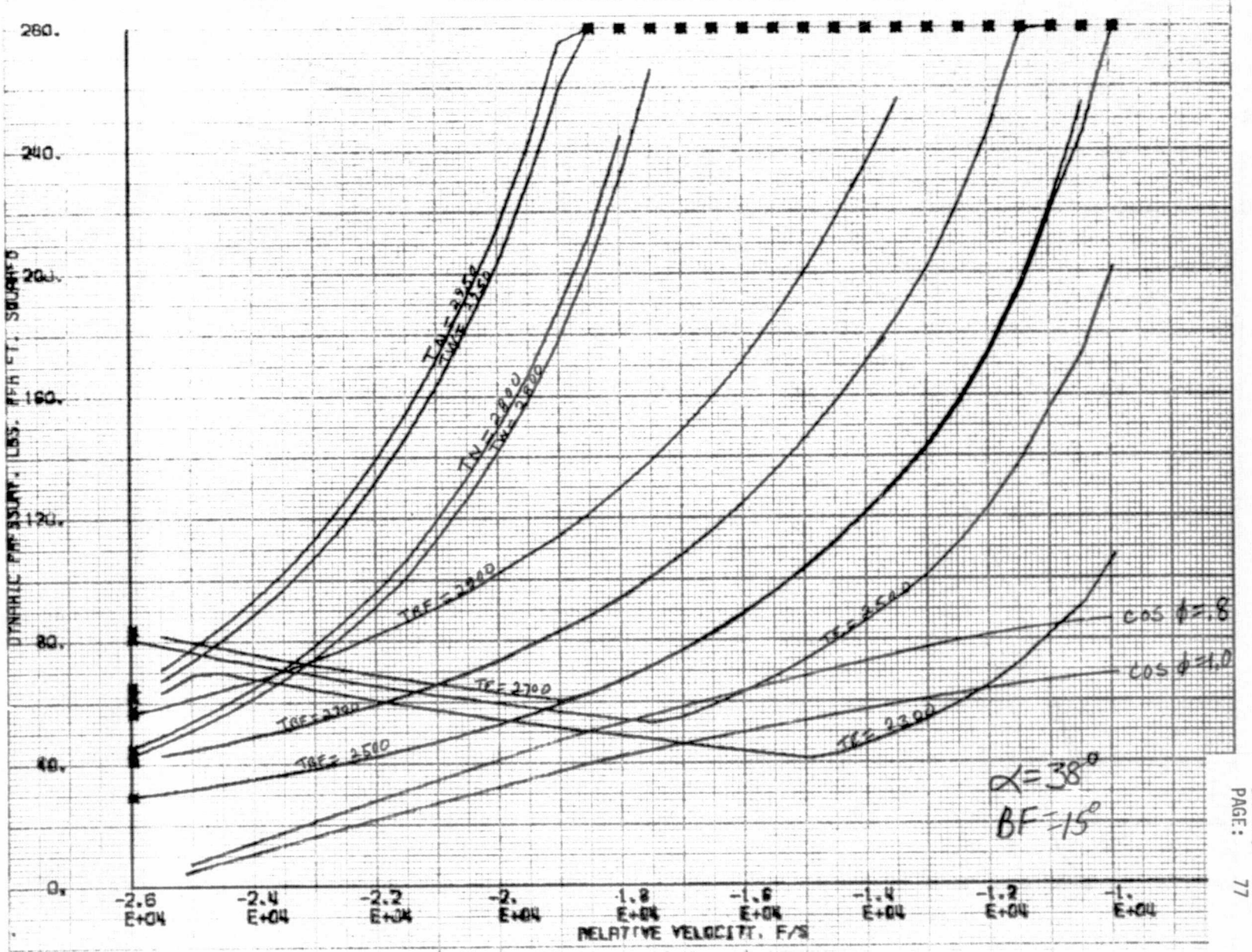


FIGURE 71 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

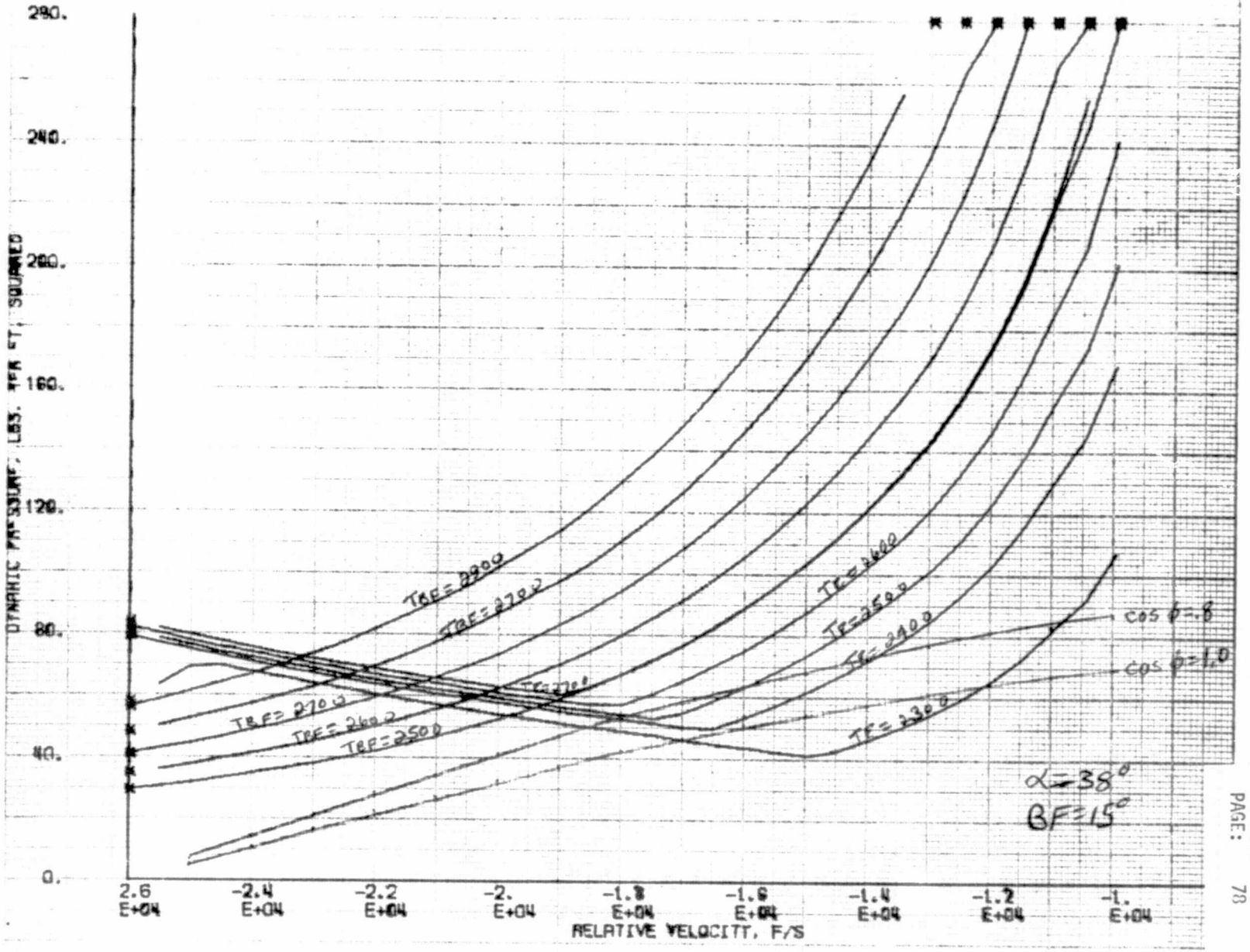


FIGURE 72 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

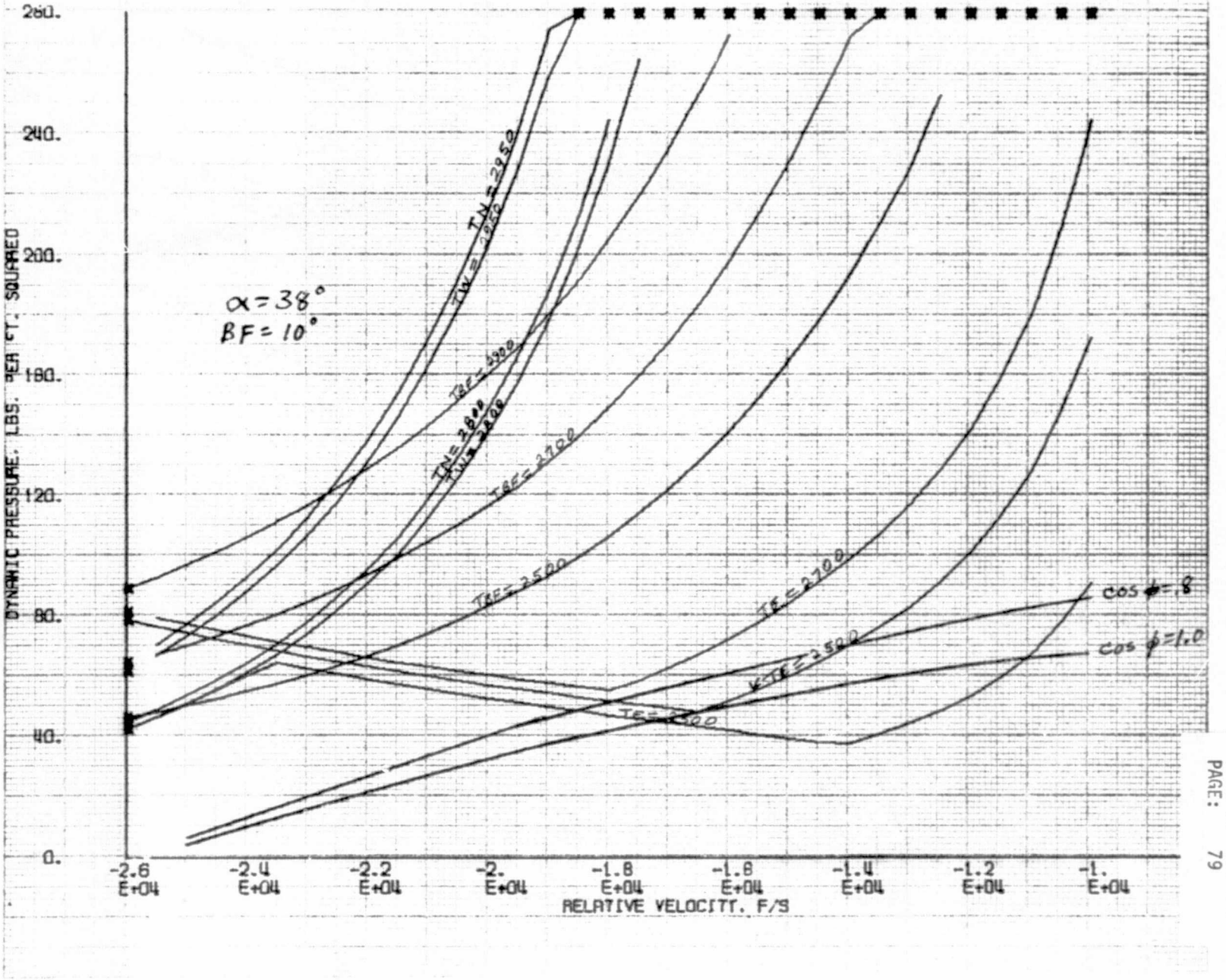


FIGURE 73 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

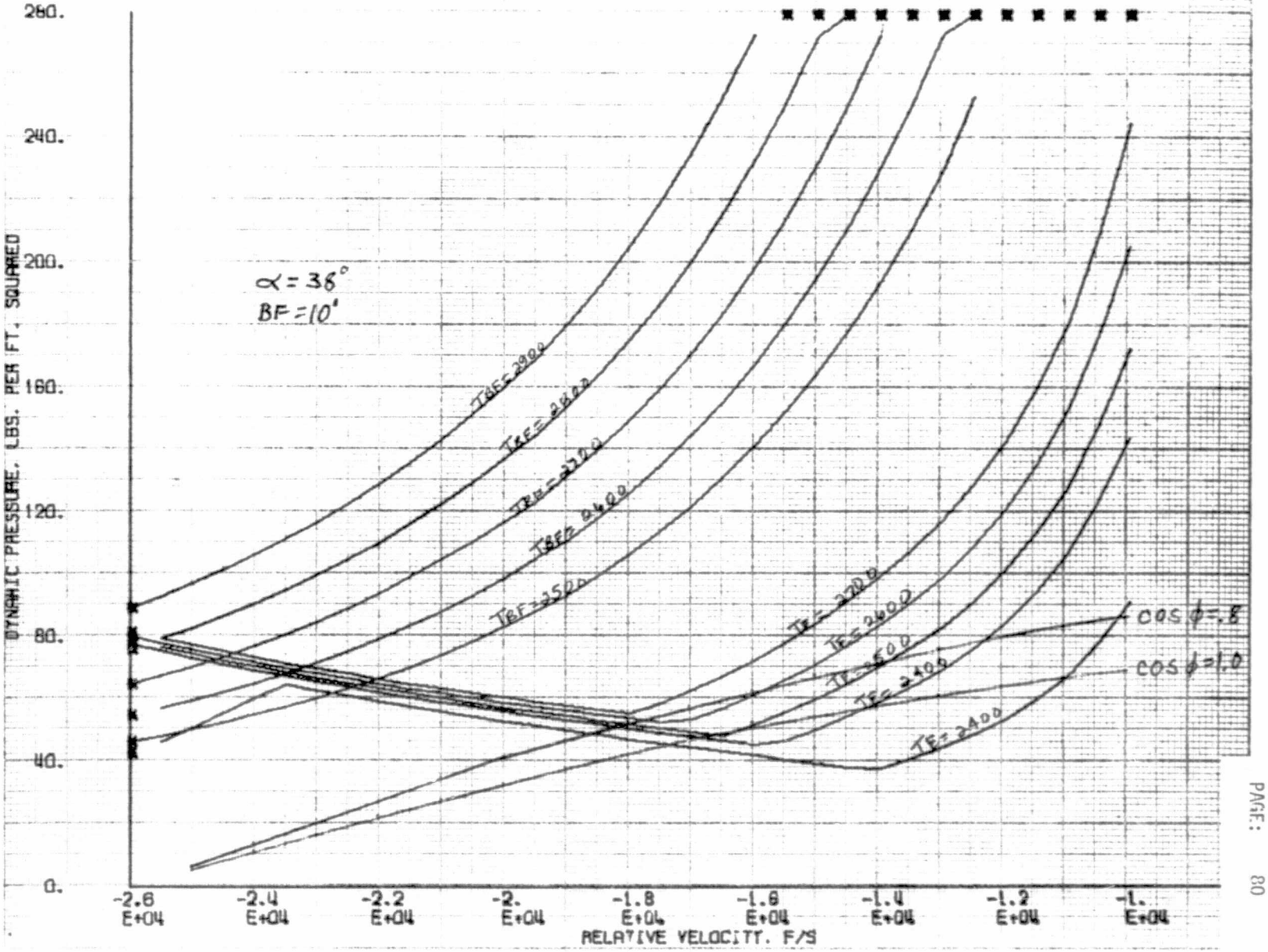


FIGURE 74 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

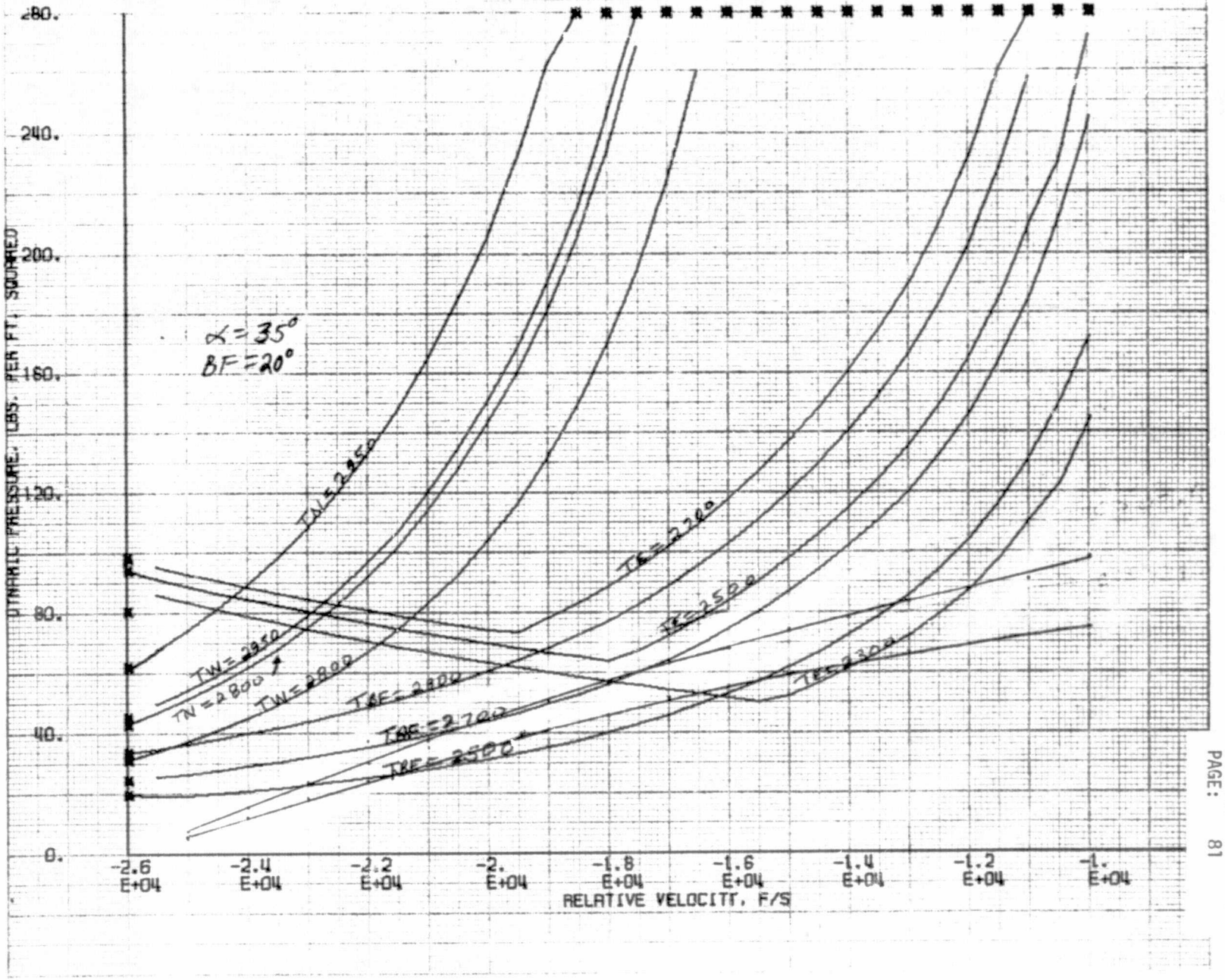


FIGURE 75 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

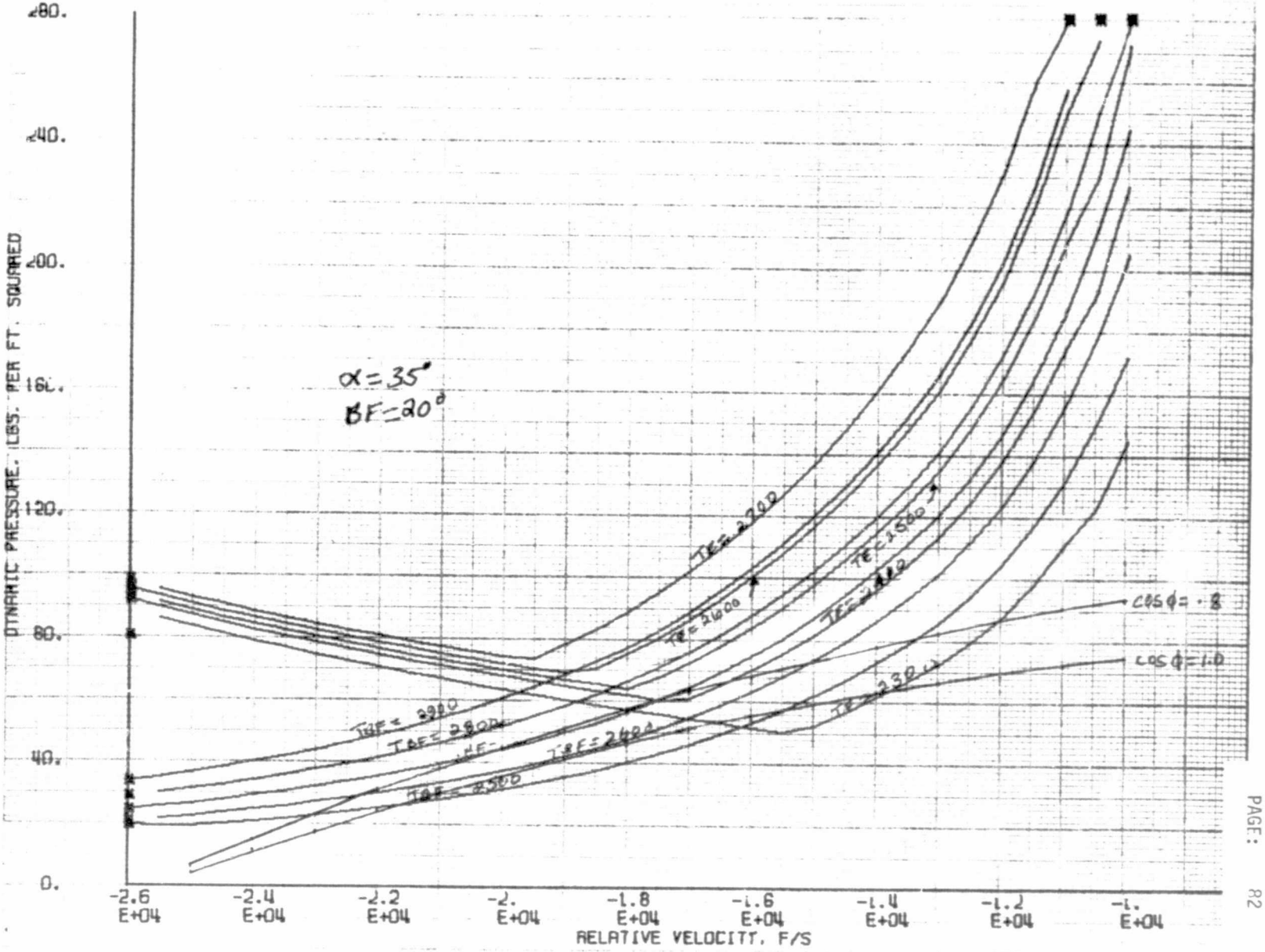


FIGURE 76 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

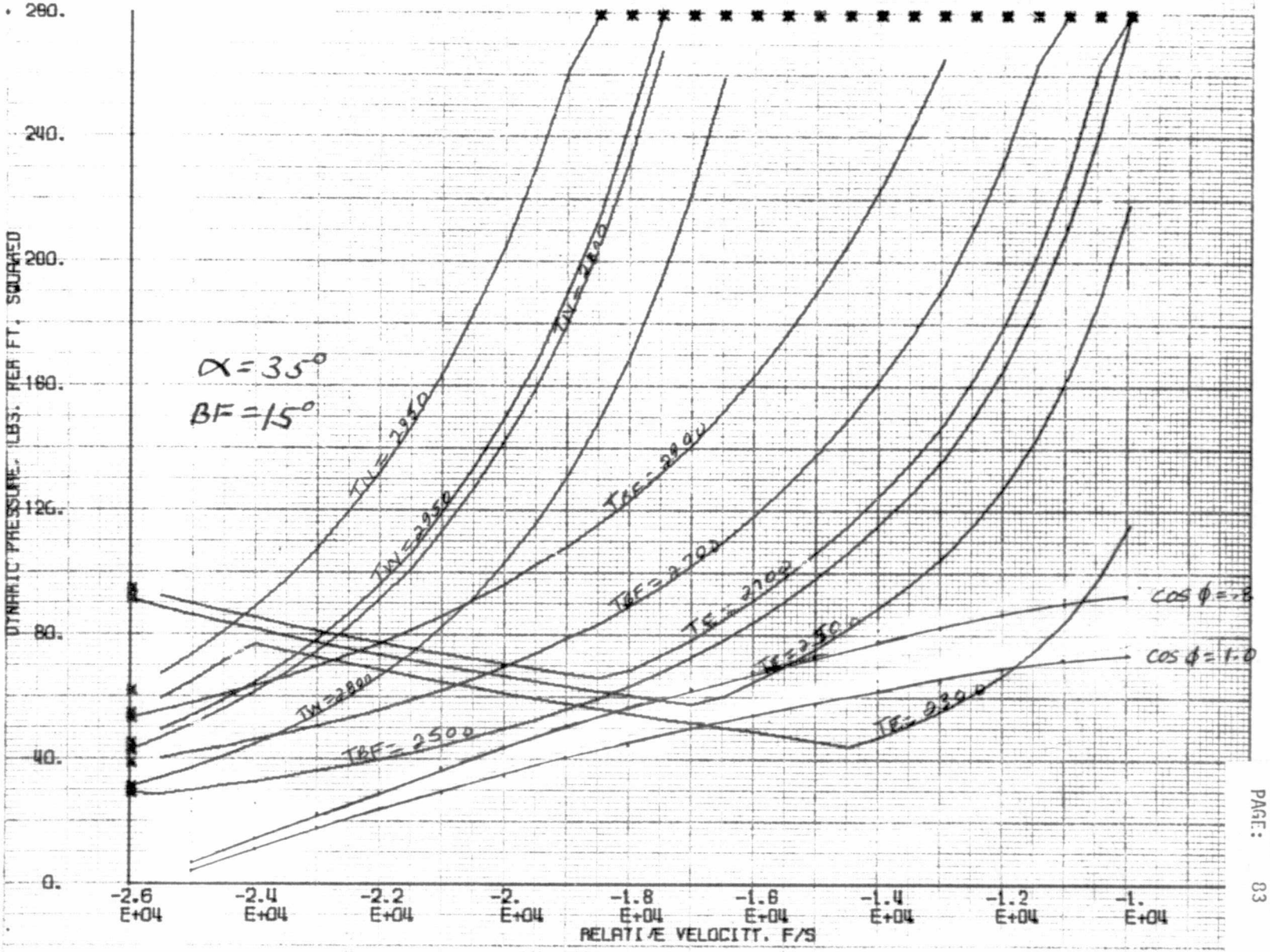


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FIGURE 77 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

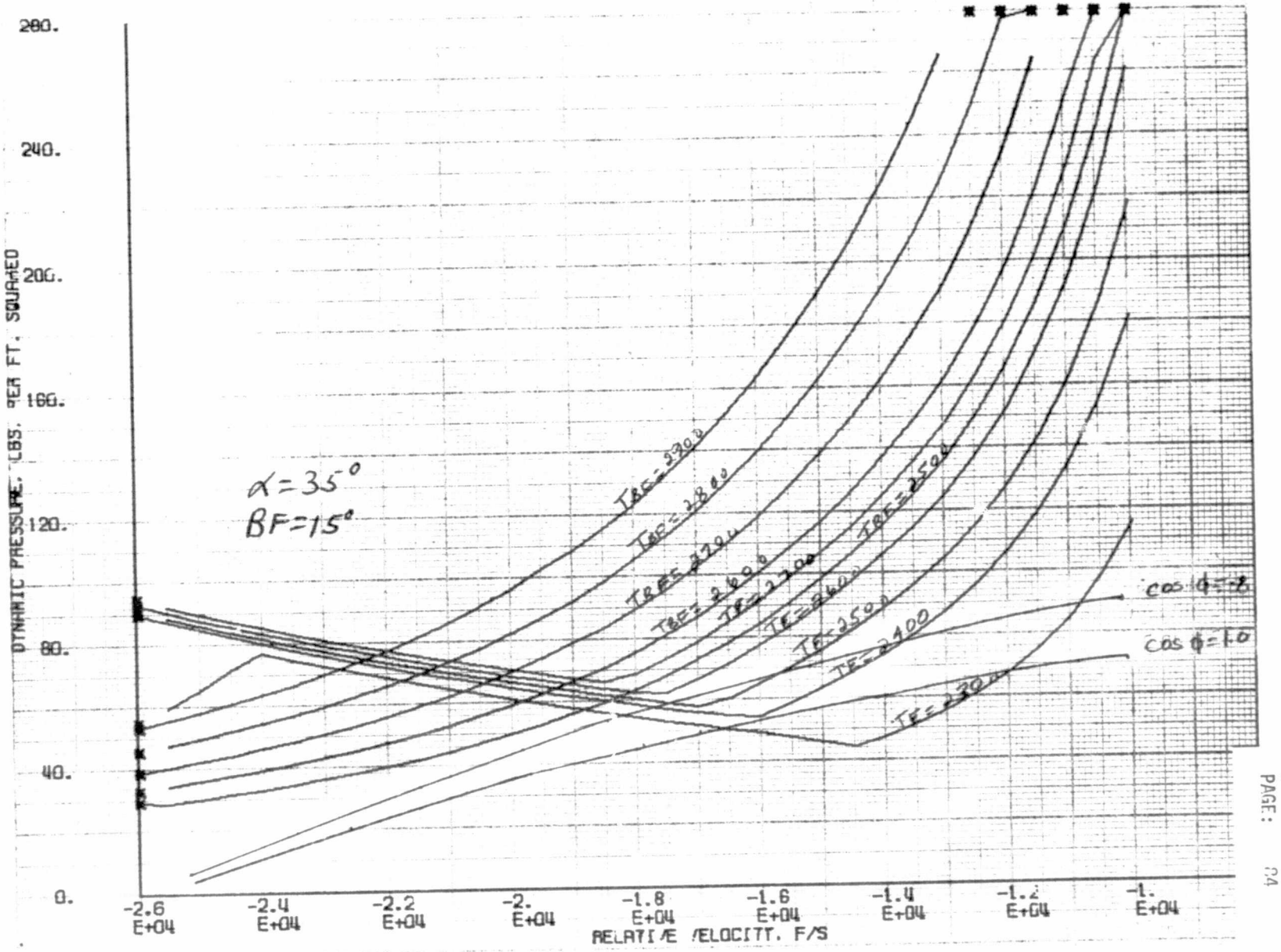

FIGURE 78 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

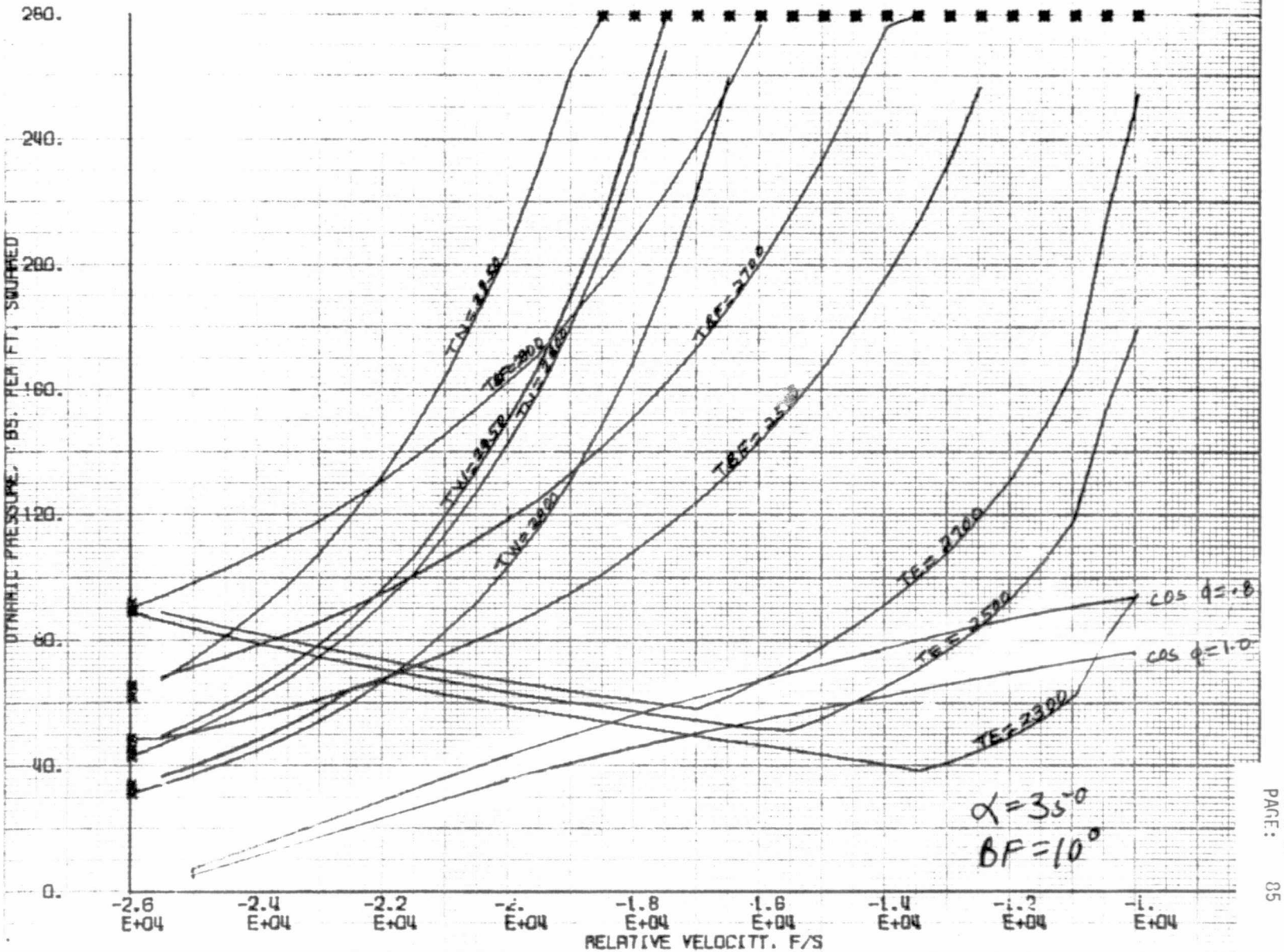

FIGURE 79 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

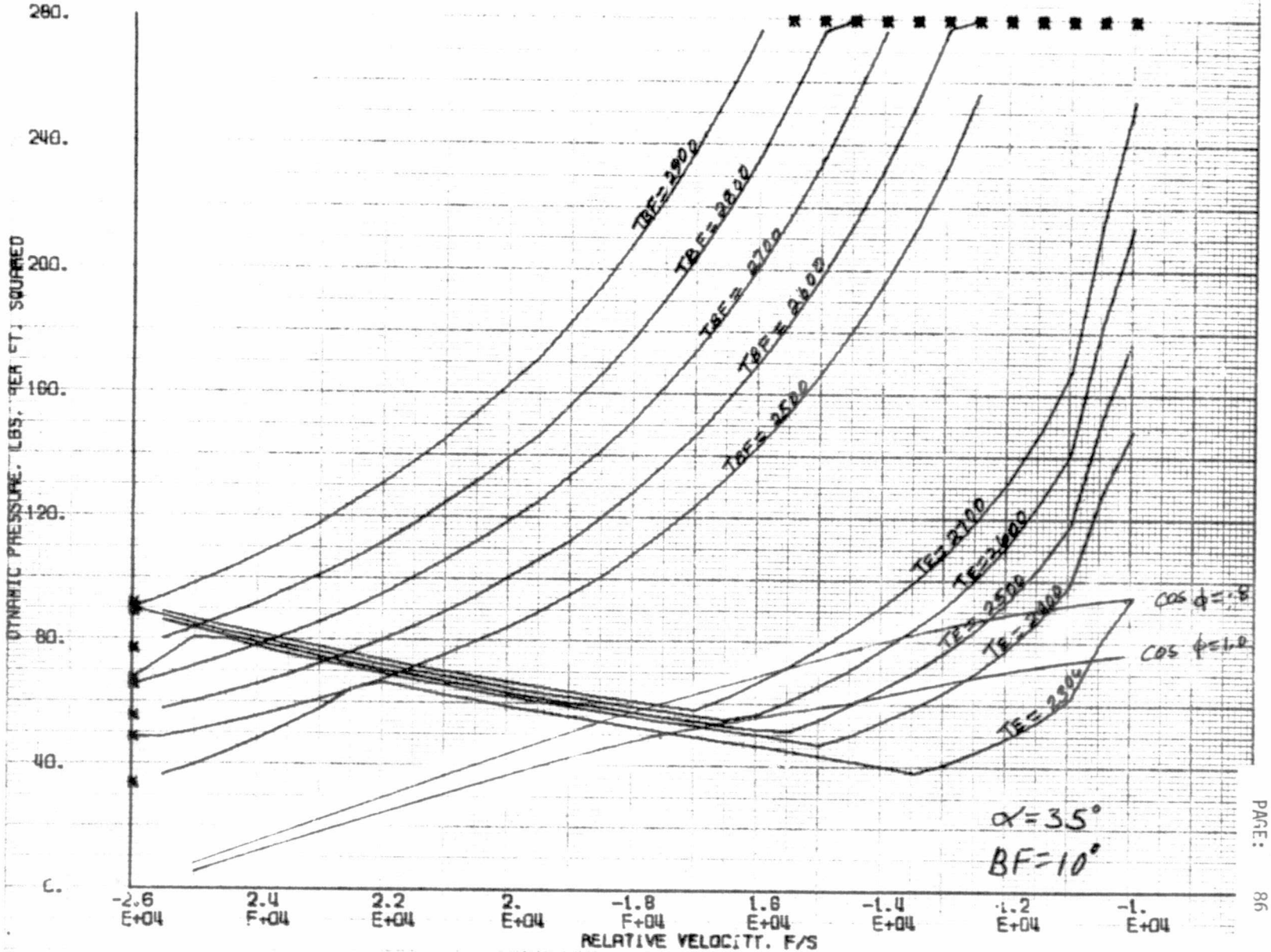

FIGURE 80 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

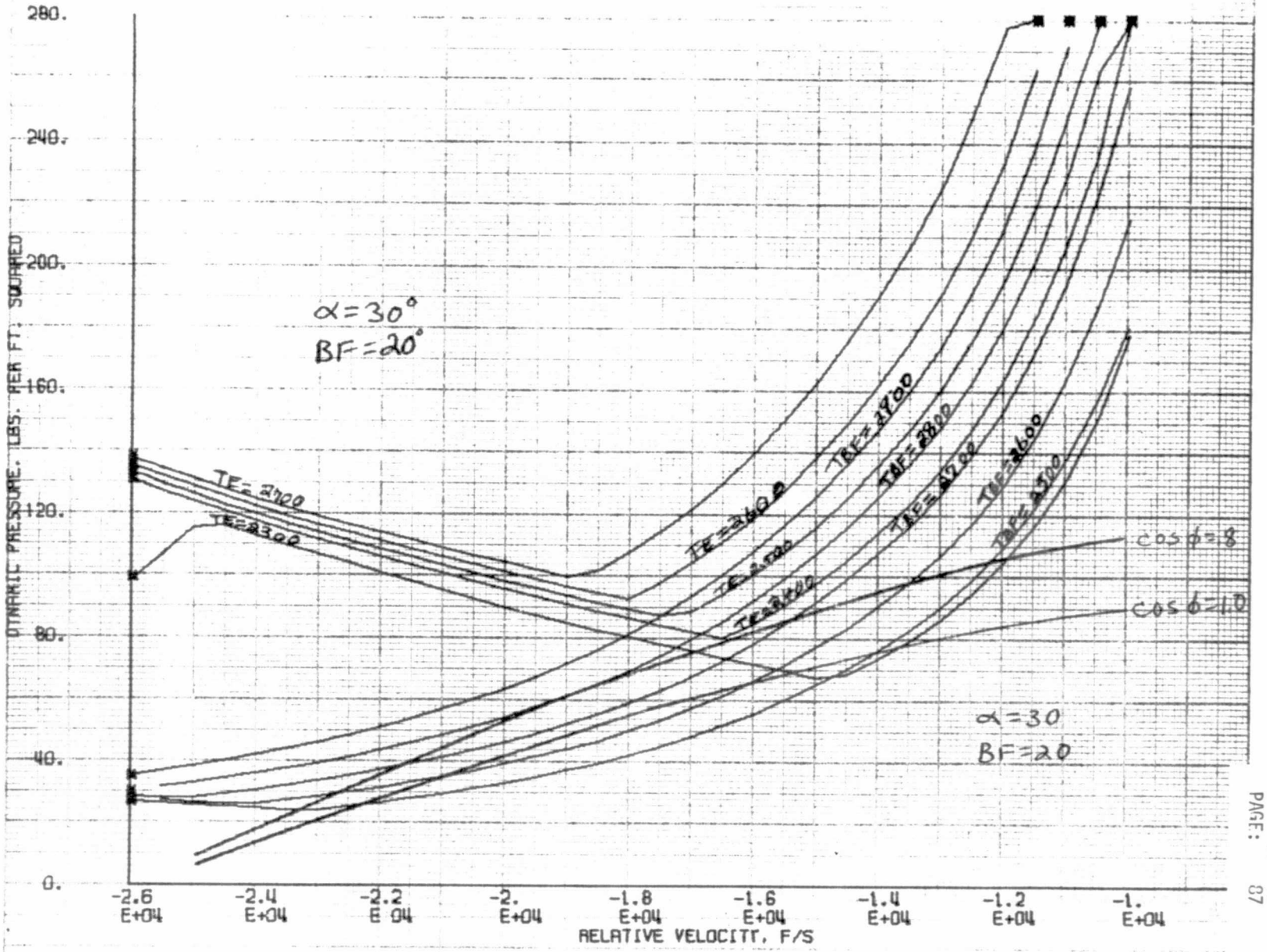

FIGURE 81 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

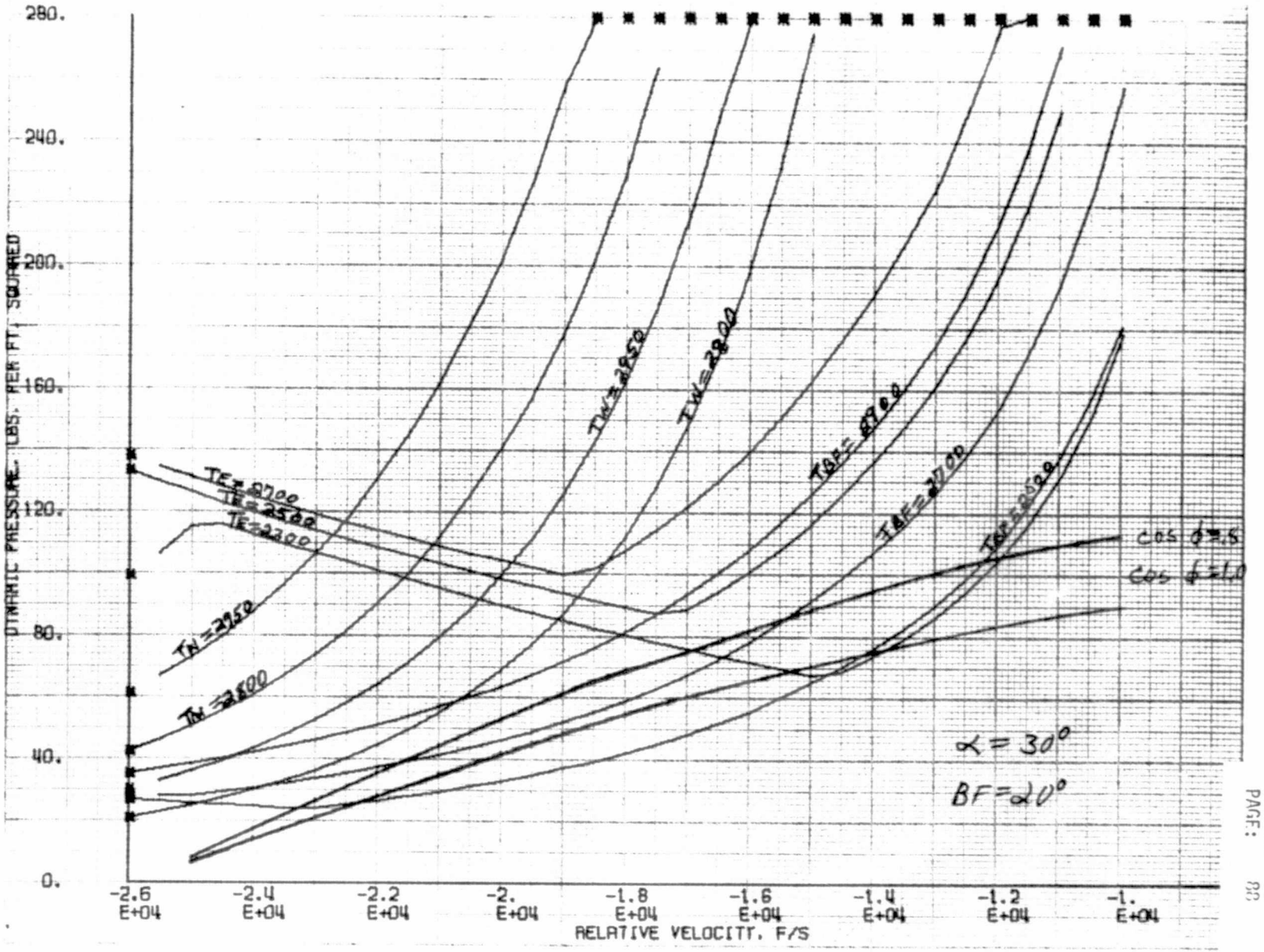

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FIGURE 82 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

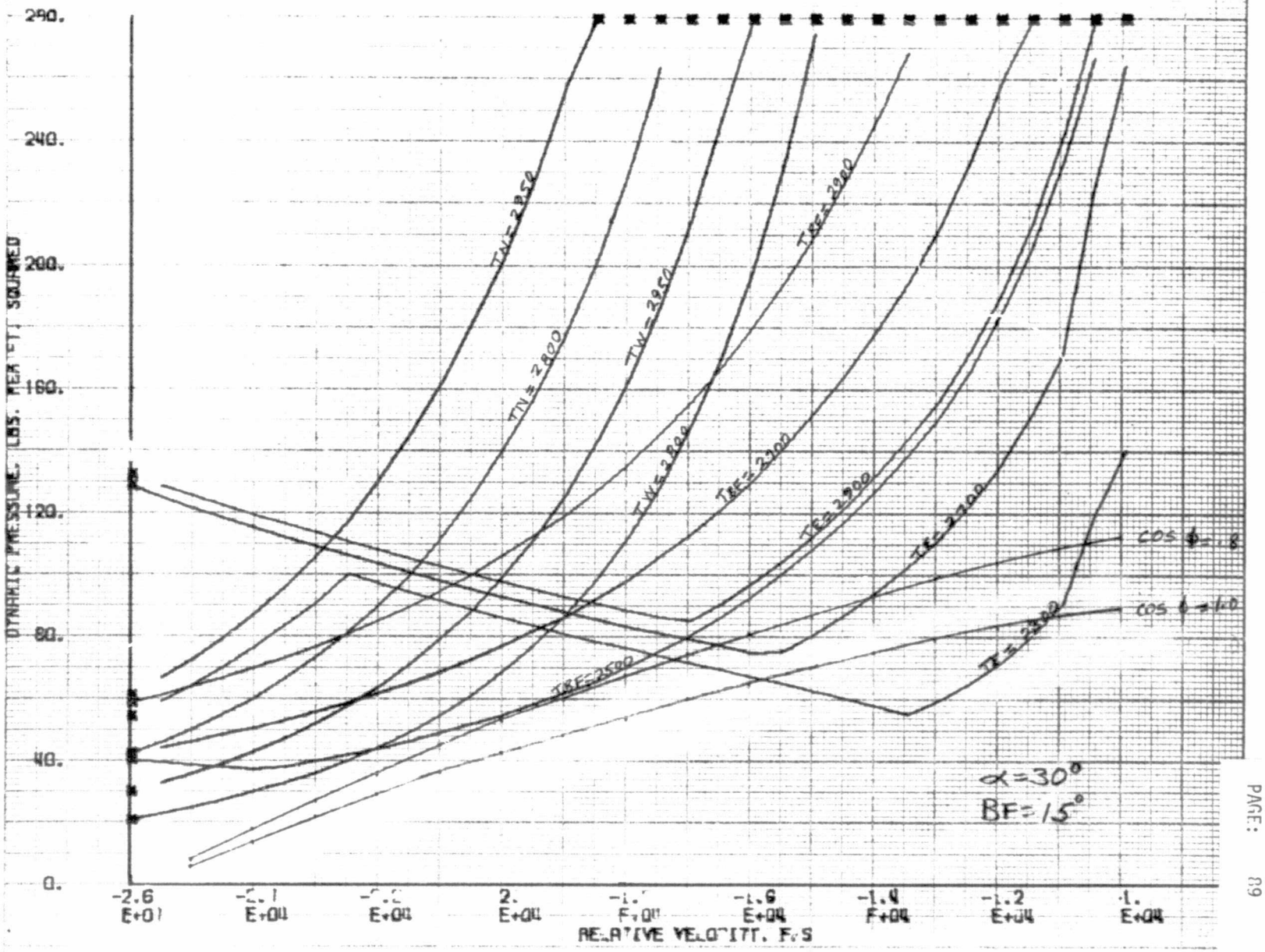

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FIGURE 83 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

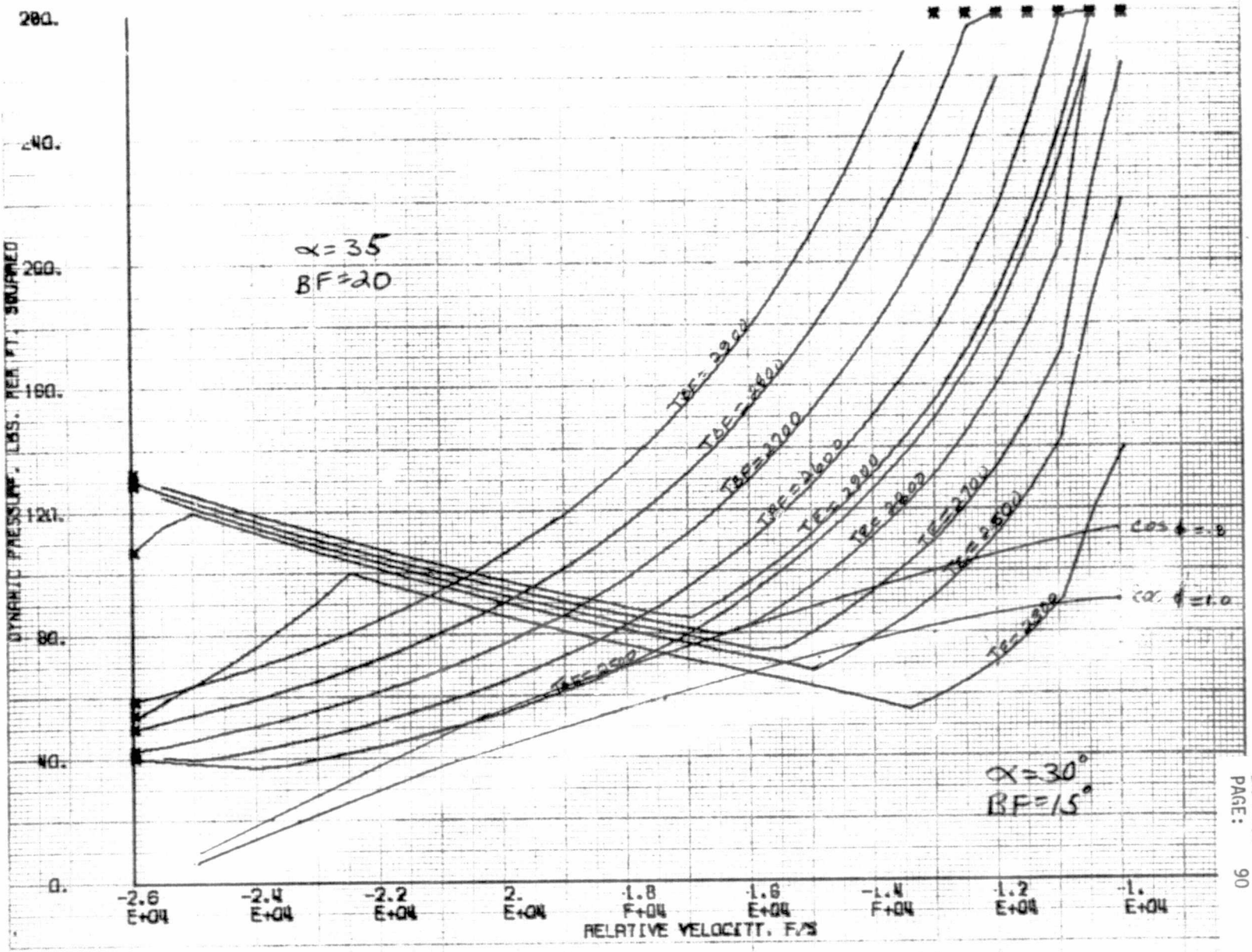
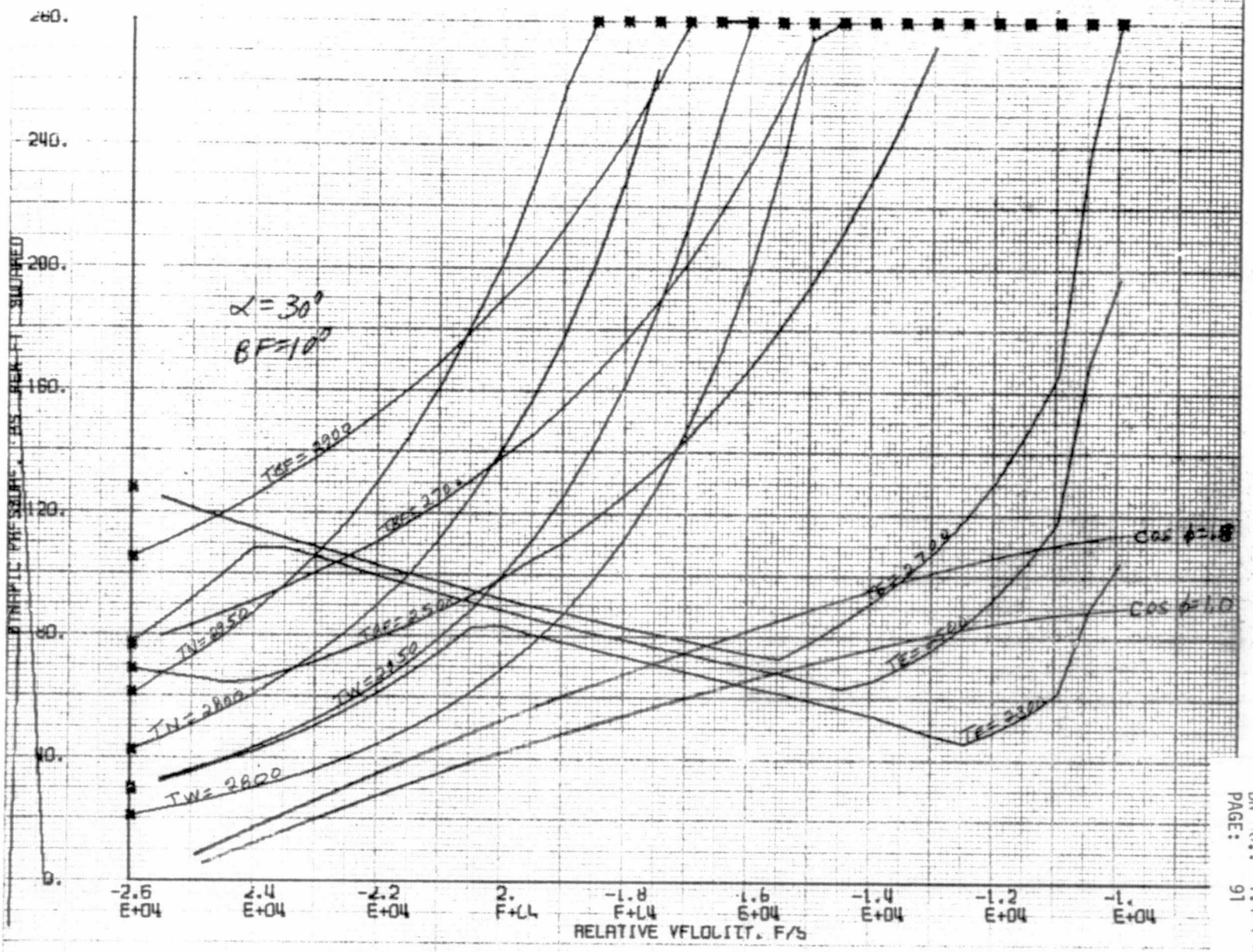


FIGURE 84 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR



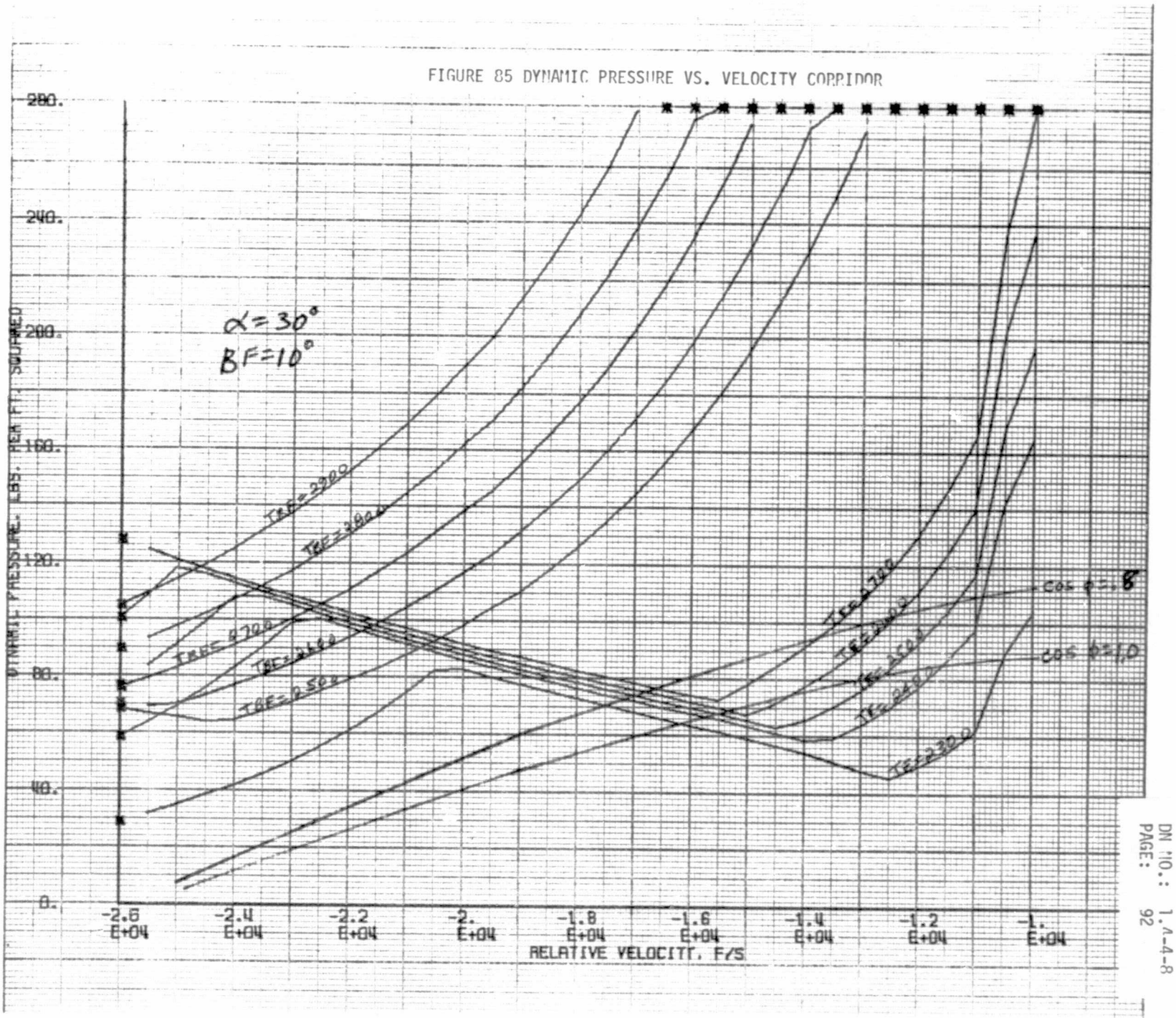


FIGURE 85 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR
DYNAMIC PRESSURE, LBS. PER FT. SQUARED
280.
240.
200.
160.
120.
80.
40.
0.
α=30°
BF=10°
TAE=2200
TAE=2000
TAE=1700
TAE=1400
TAE=1100
TAE=800
TAE=500
cos φ=.8
cos φ=1.0
-2.6 E+04
-2.4 E+04
-2.2 E+04
-2. E+04
-1.8 E+04
-1.6 E+04
-1.4 E+04
-1.2 E+04
-1. E+04
RELATIVE VELOCITY, F/S

FIGURE 86 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

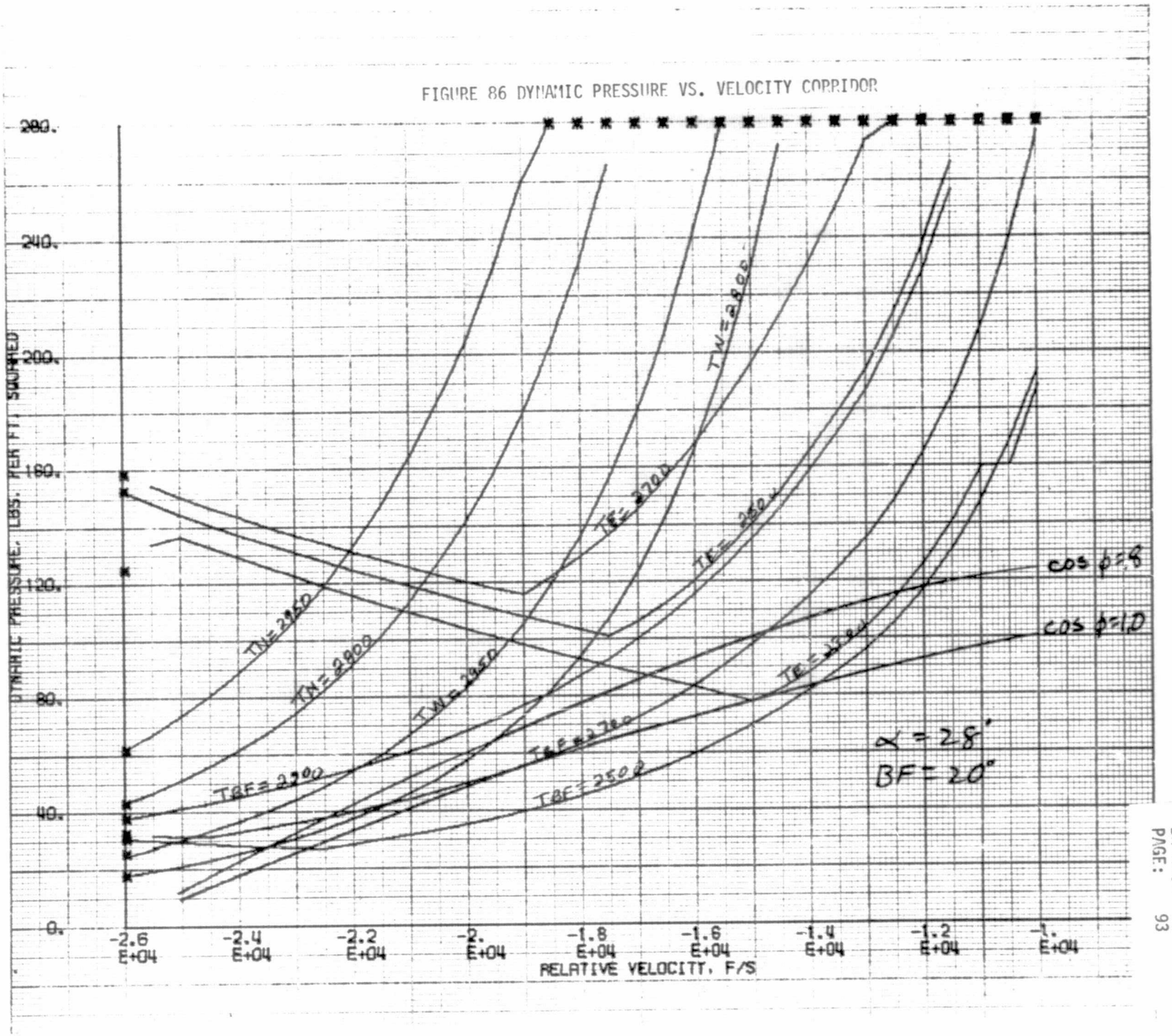


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FIGURE 87 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

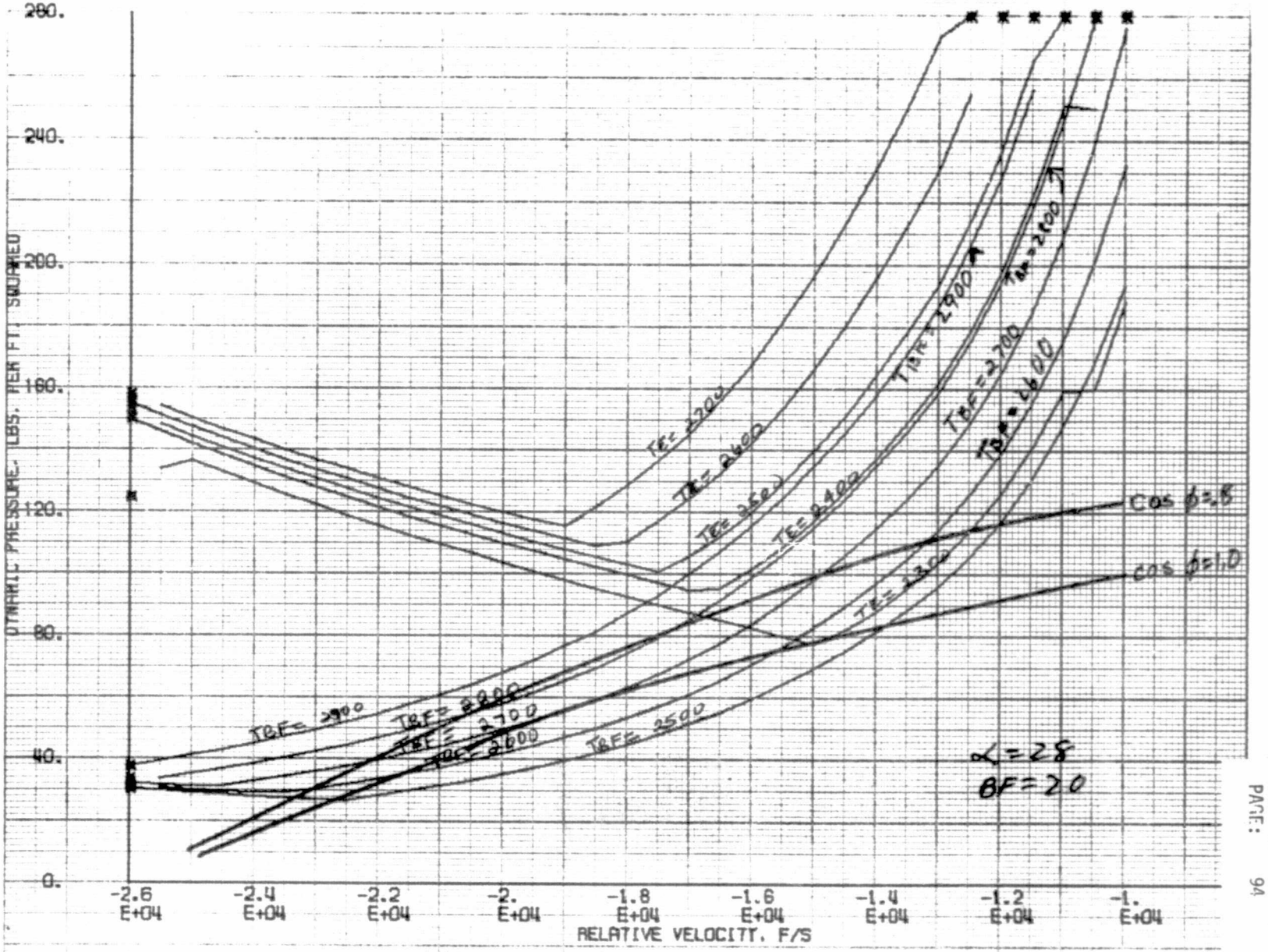


FIGURE 88 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

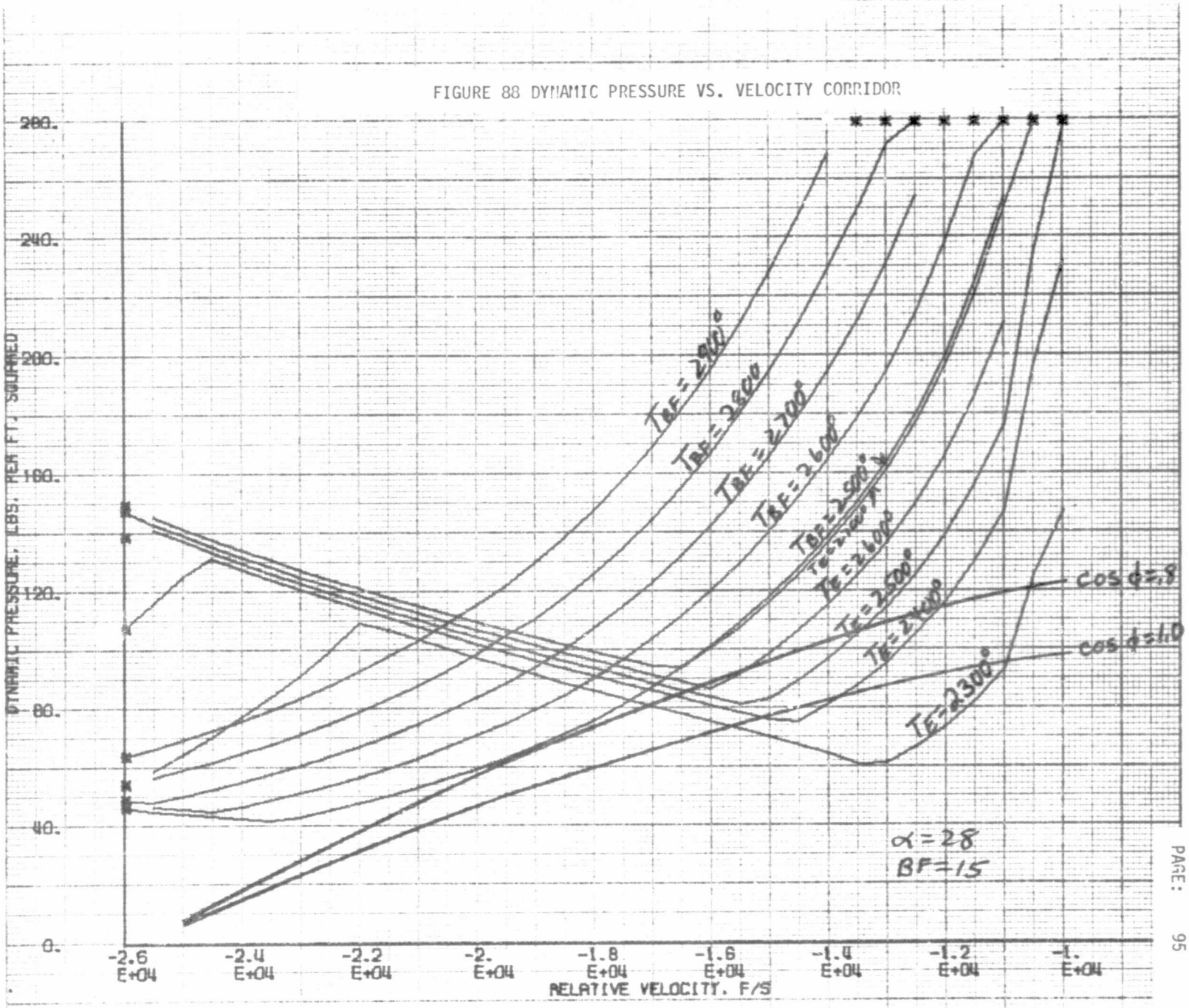
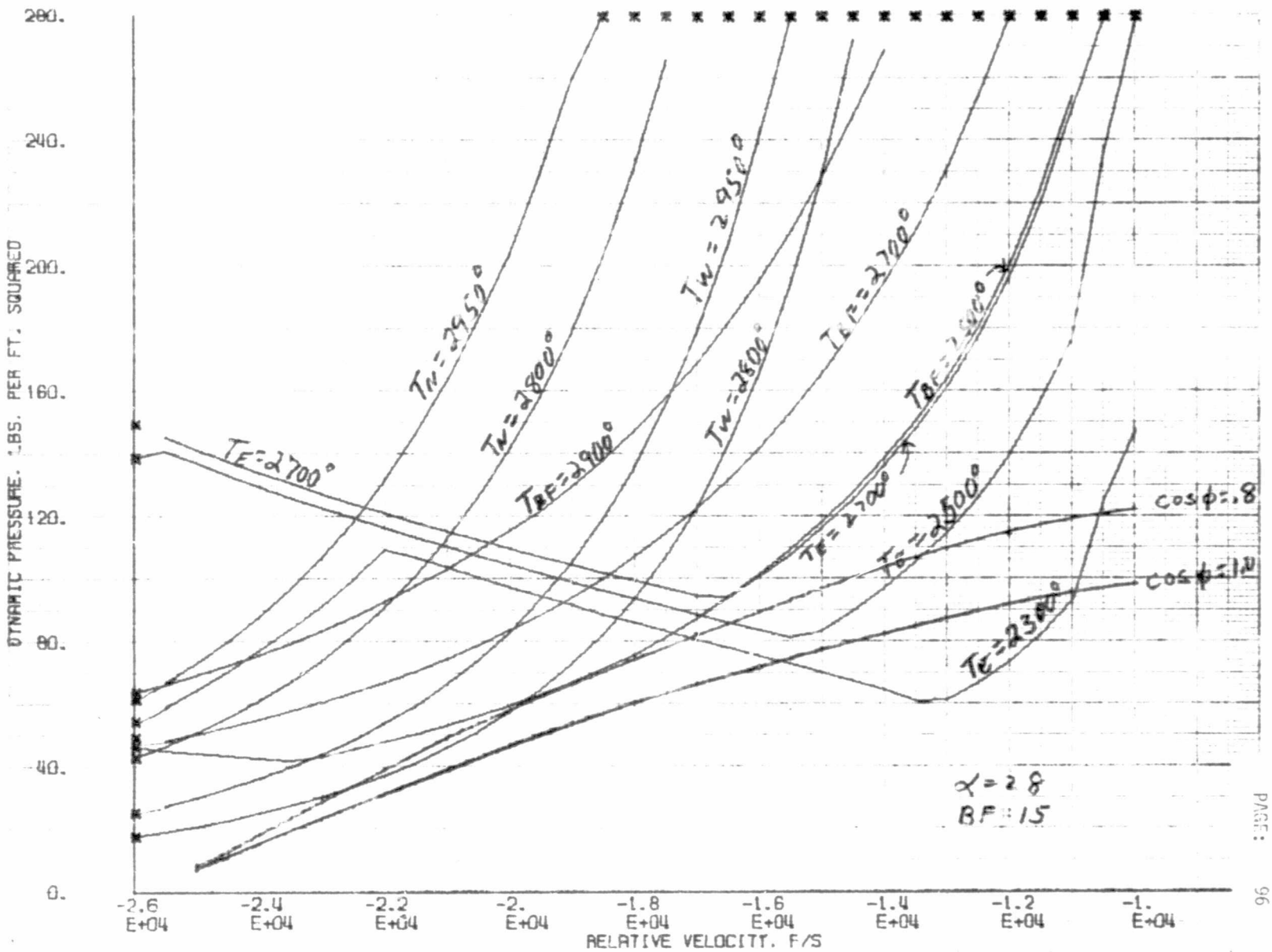


FIGURE 89 [illegible]



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C2

FIGURE 90 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

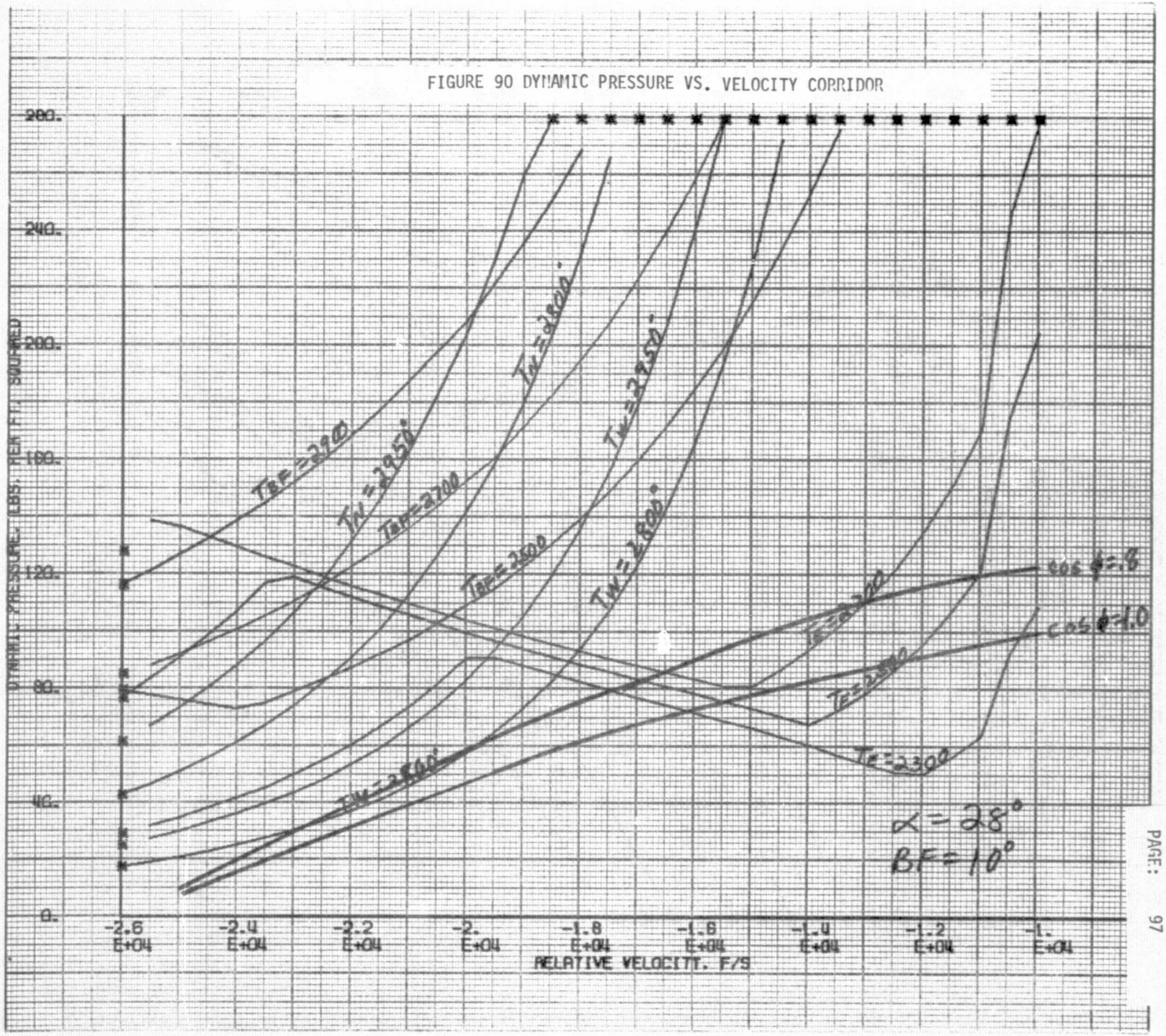

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FIGURE 91 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

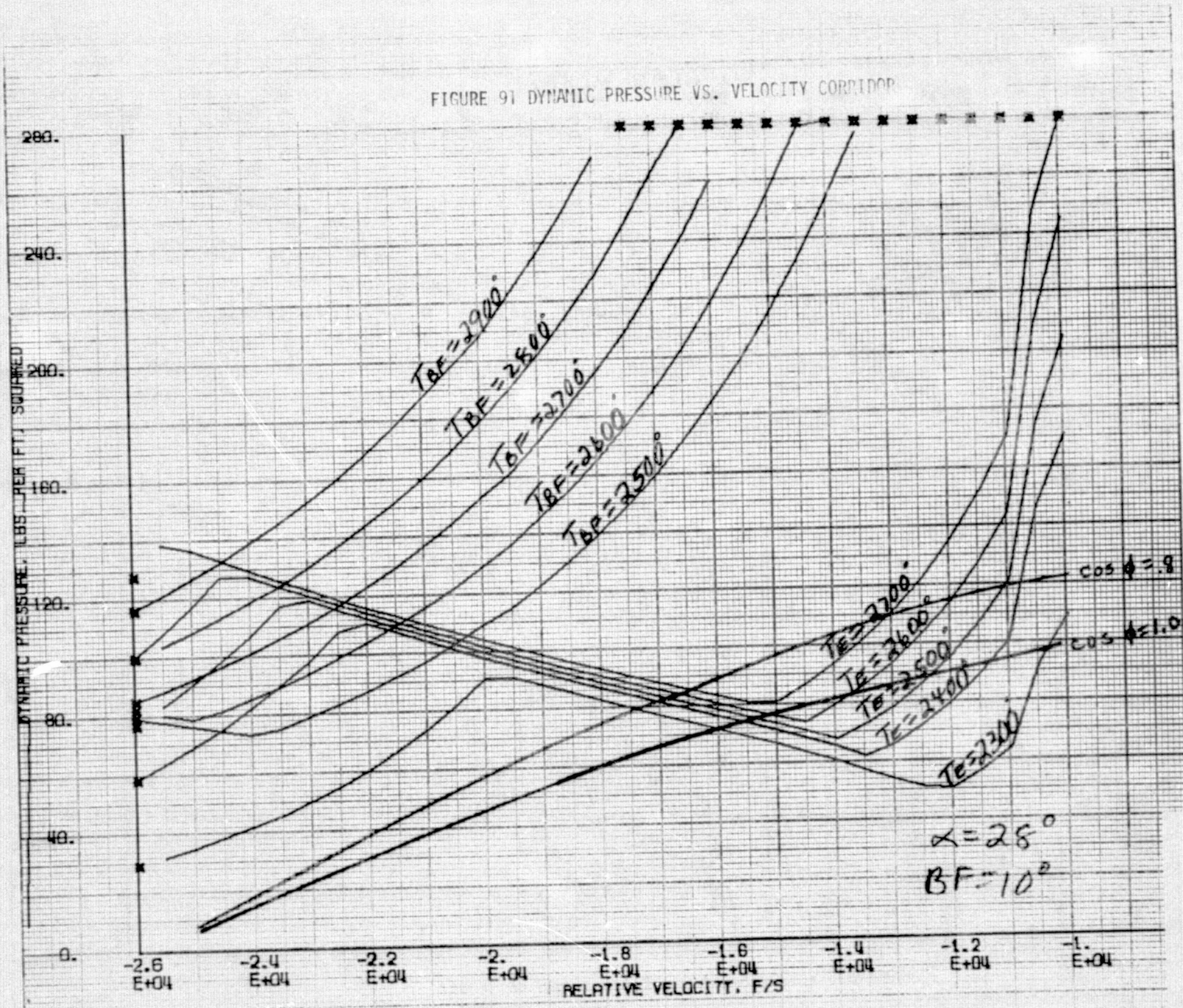

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FIGURE 92 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

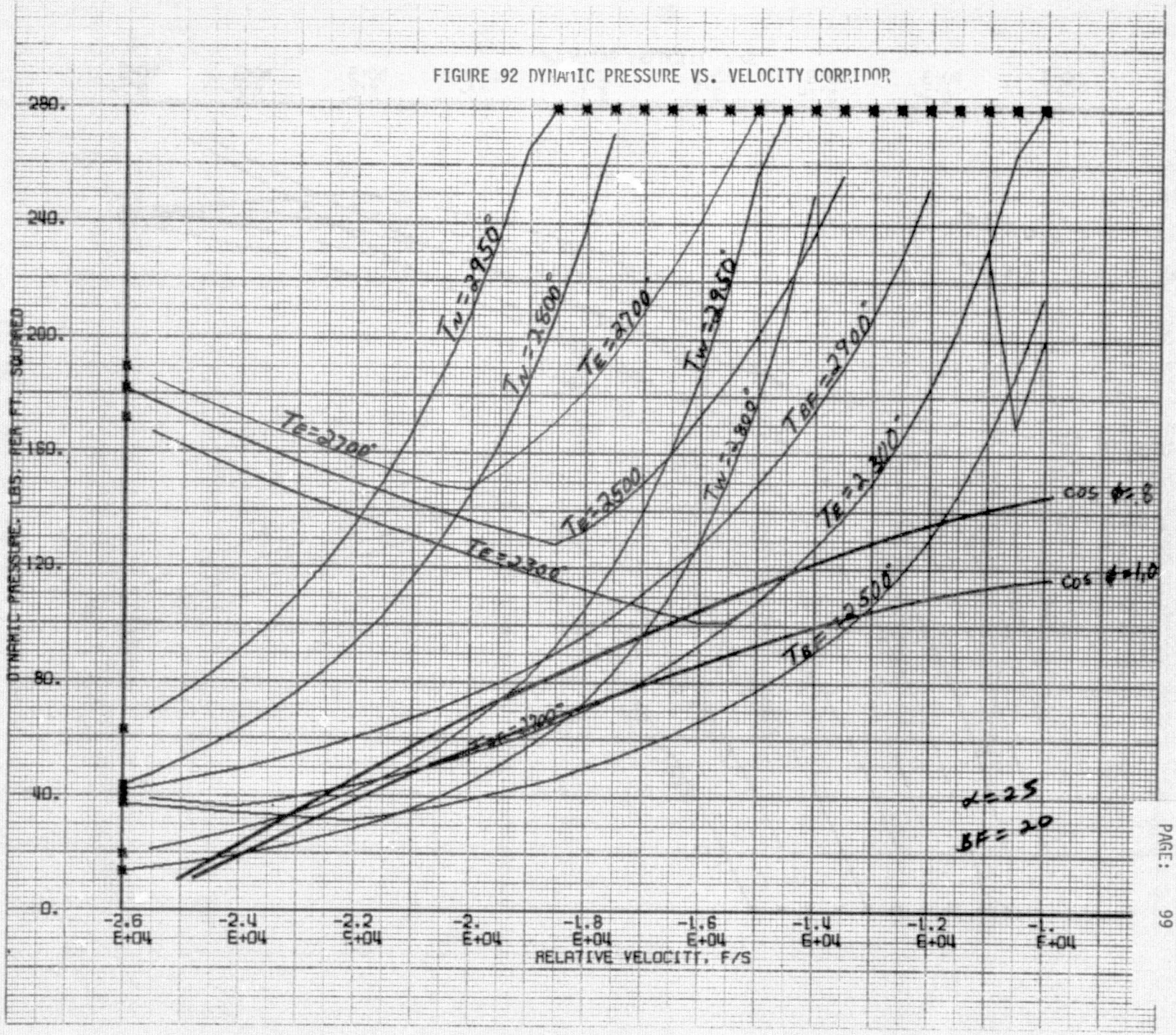

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FIGURE 93 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

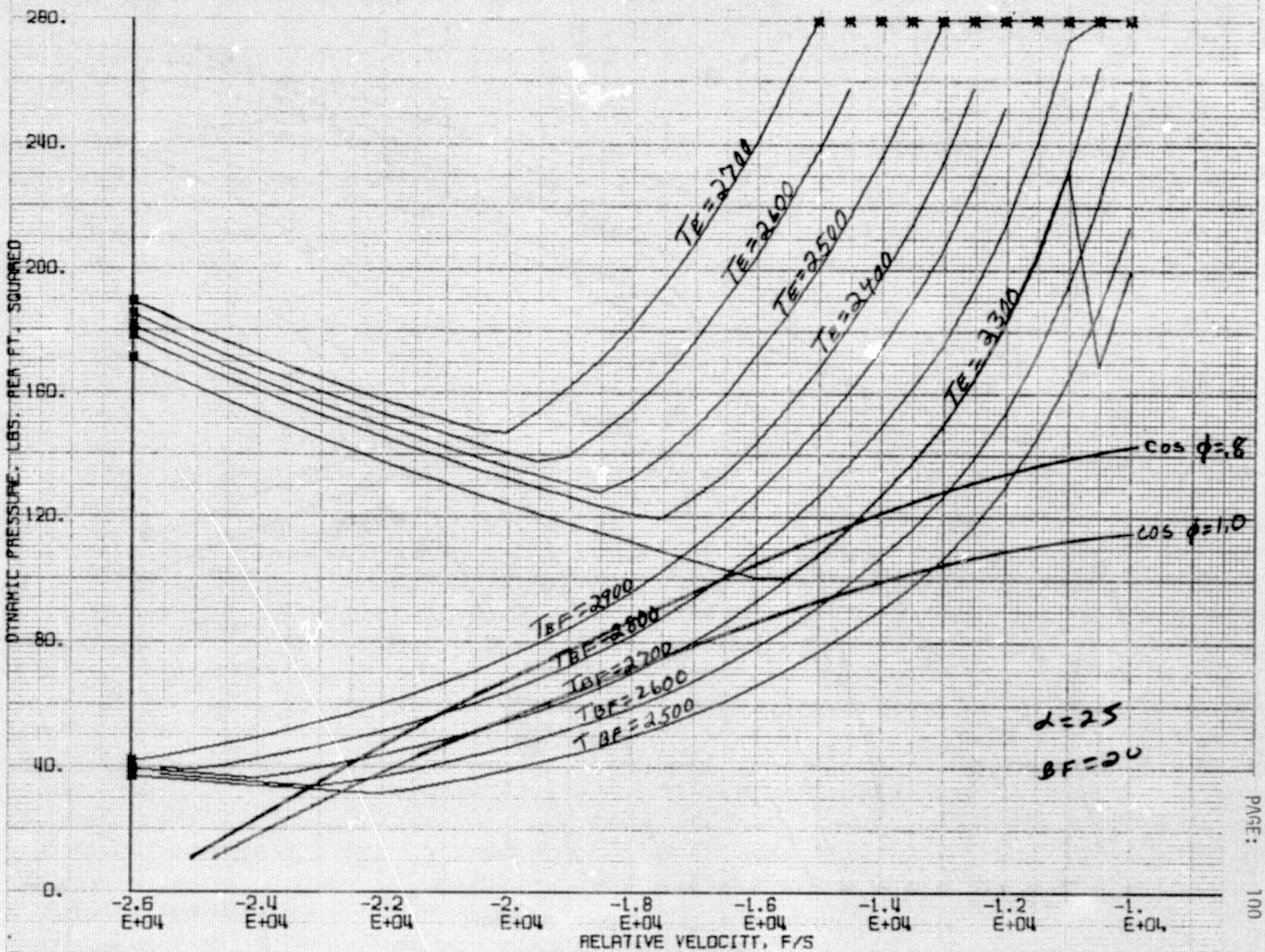

FIGURE 94 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

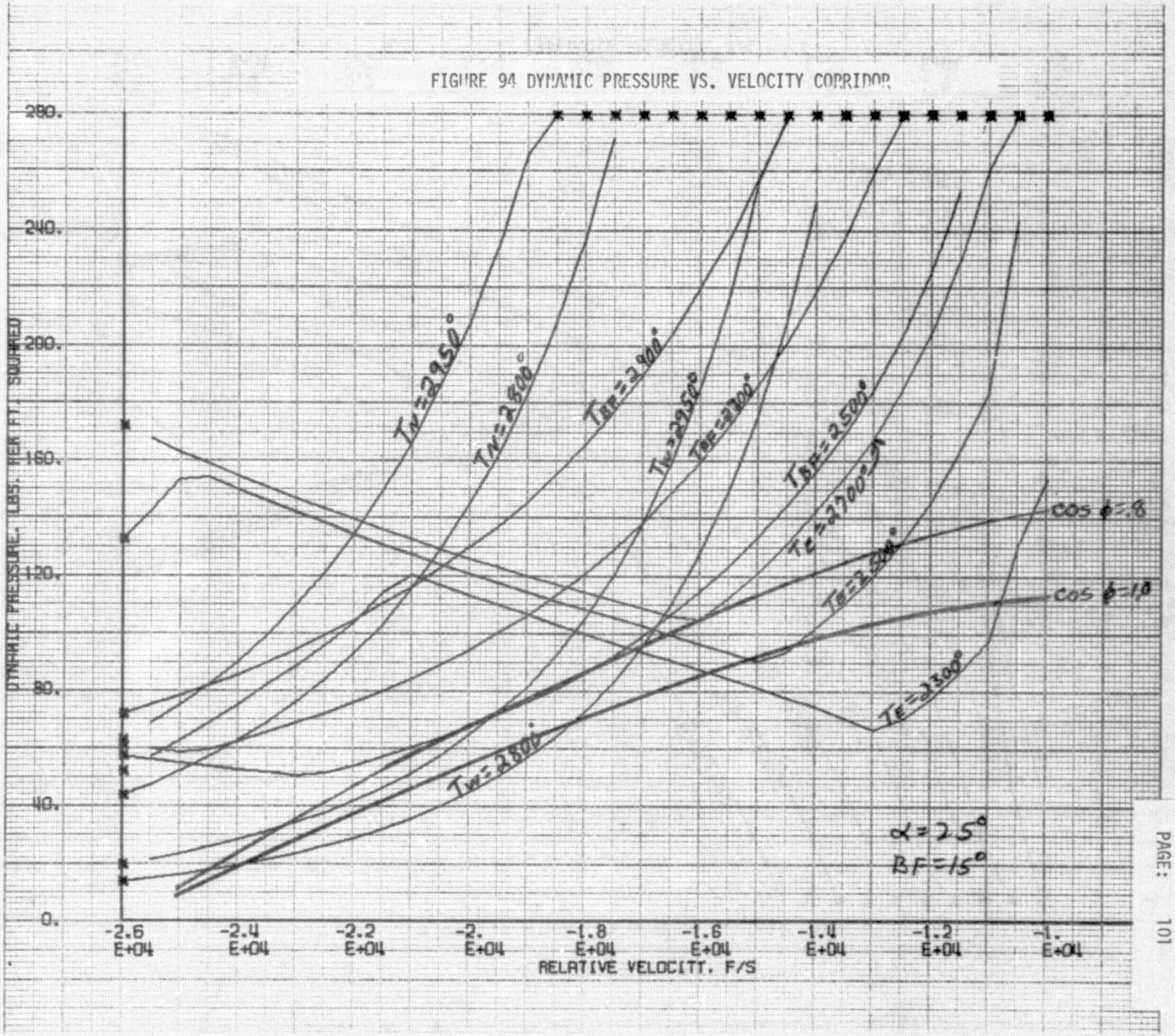

FIGURE 95 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

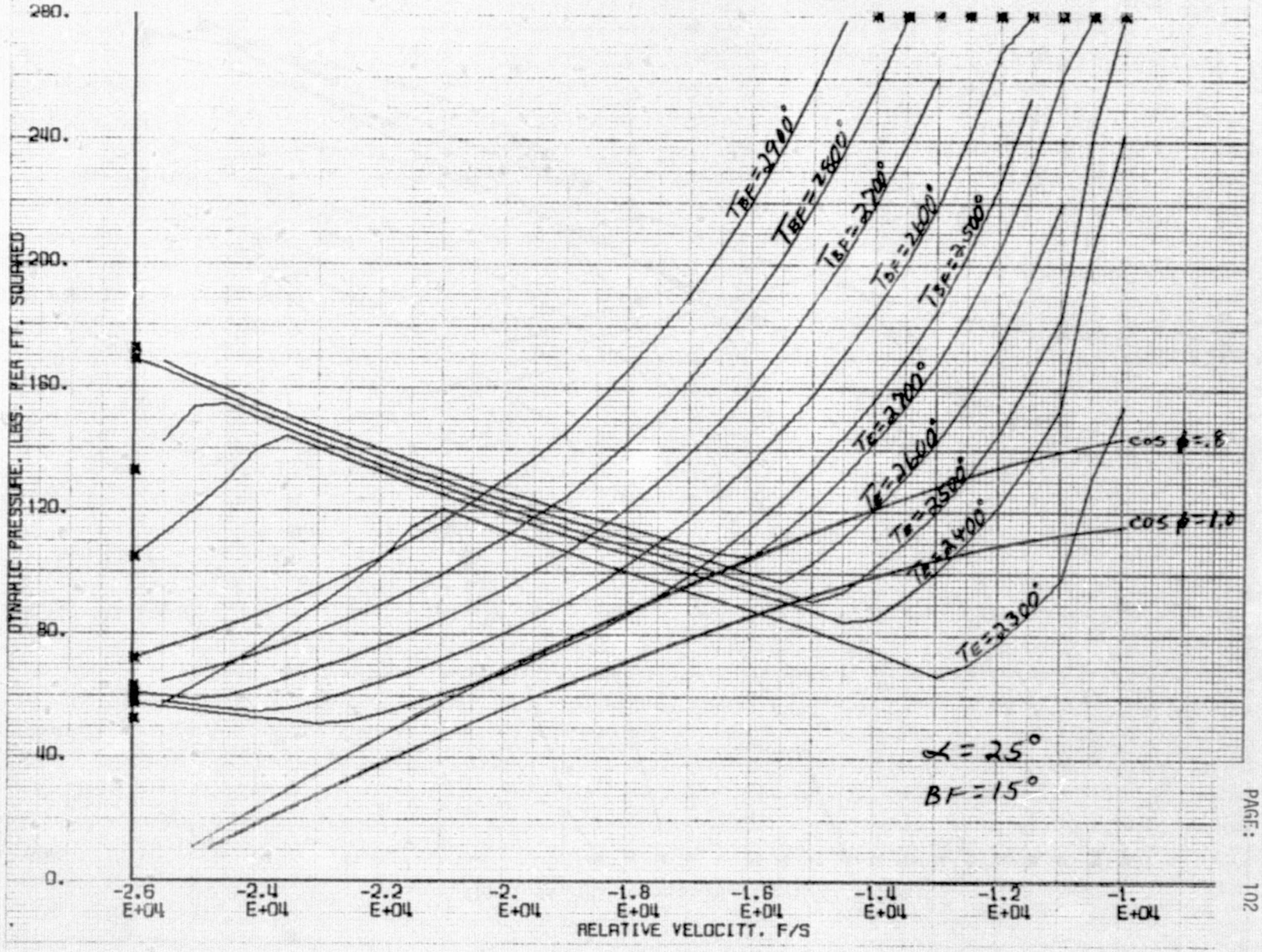

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FIGURE 96 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

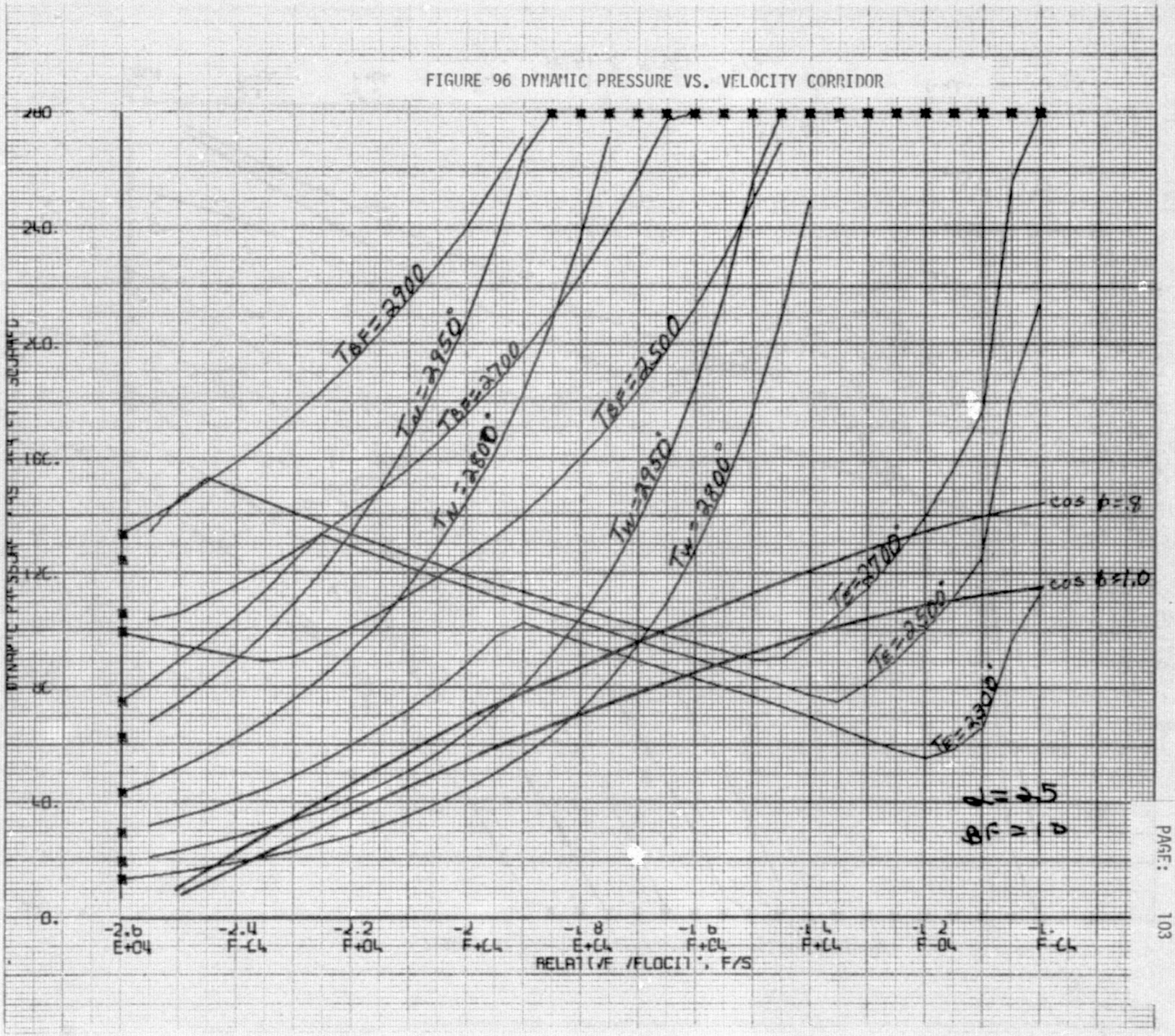

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FIGURE 97 DYNAMIC PRESSURE VS. VELOCITY CORRIDOR

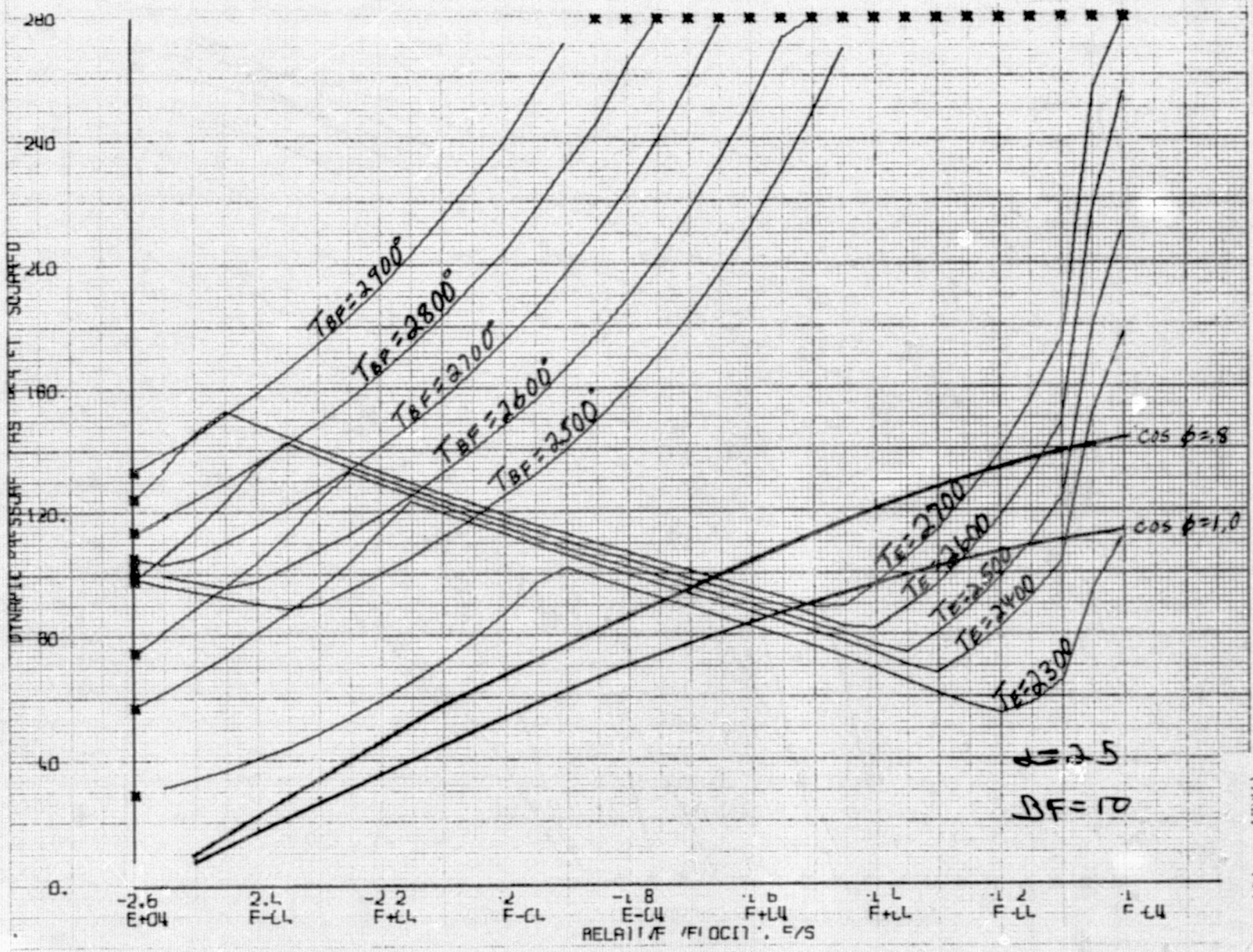

FIGURE 98 ALTITUDE VS. VELOCITY CORRIDOR

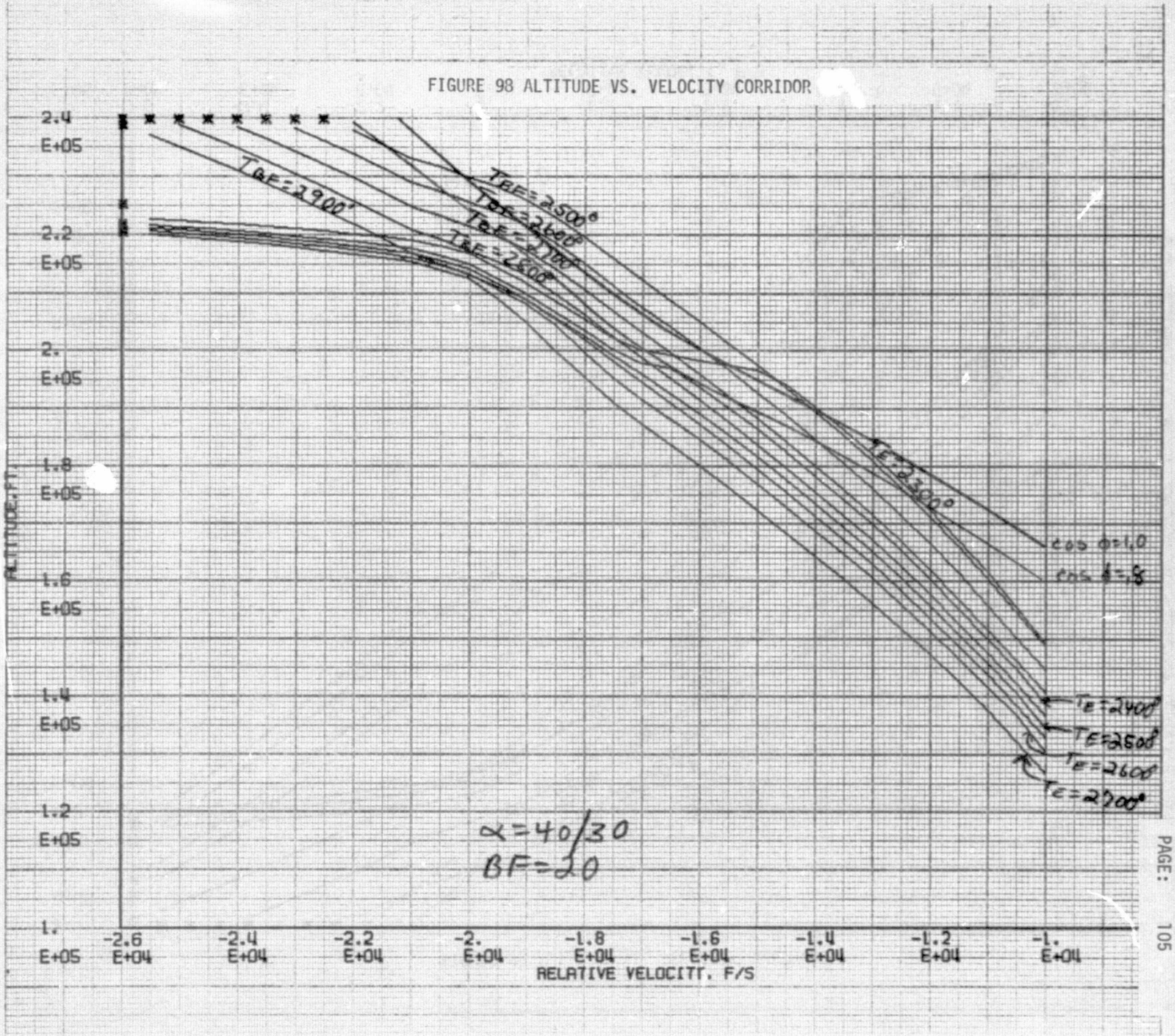

FIGURE 99 ALTITUDE VS. VELOCITY CORRIDOR

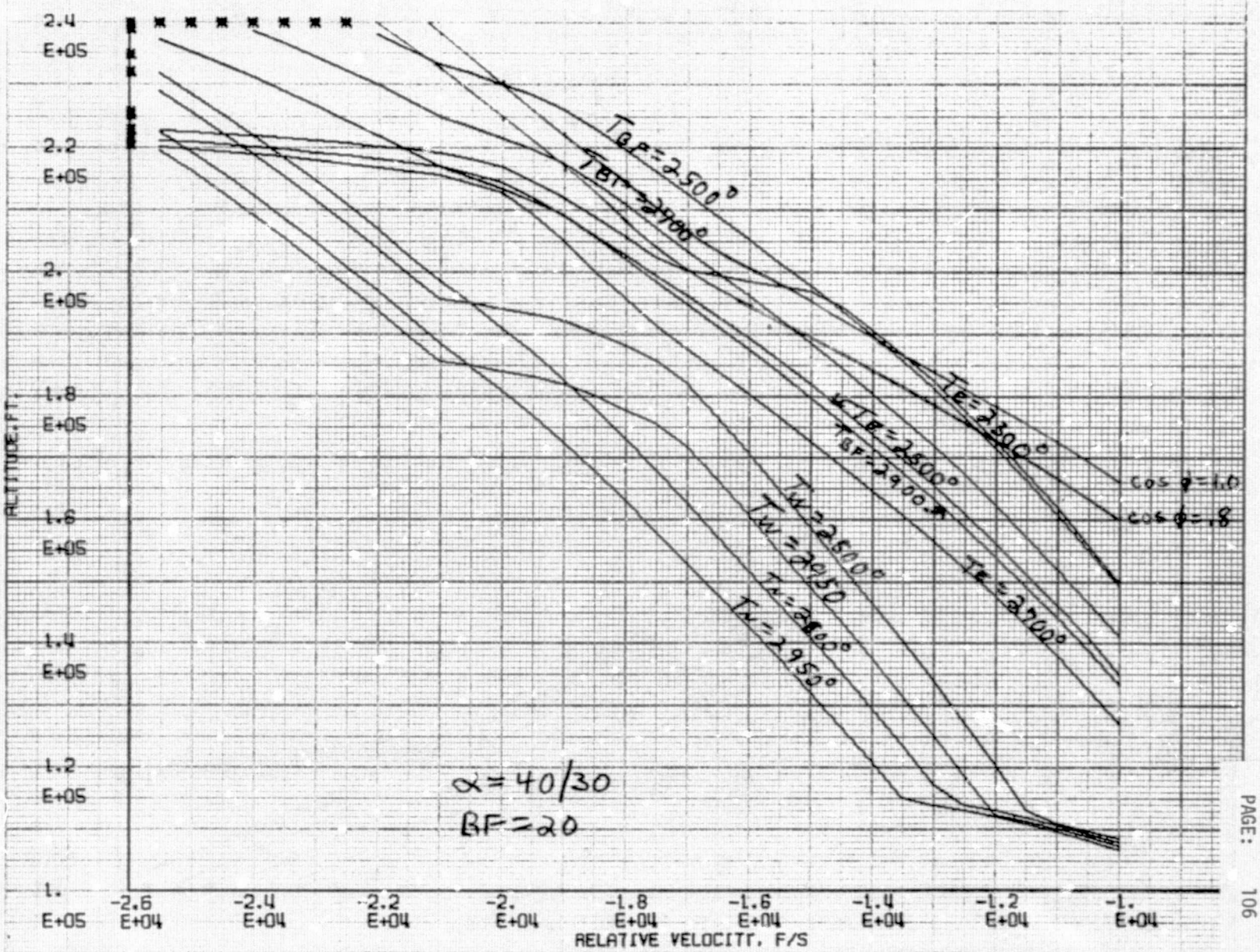

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FIGURE 100 ALTITUDE VS. VELOCITY CORRIDOR

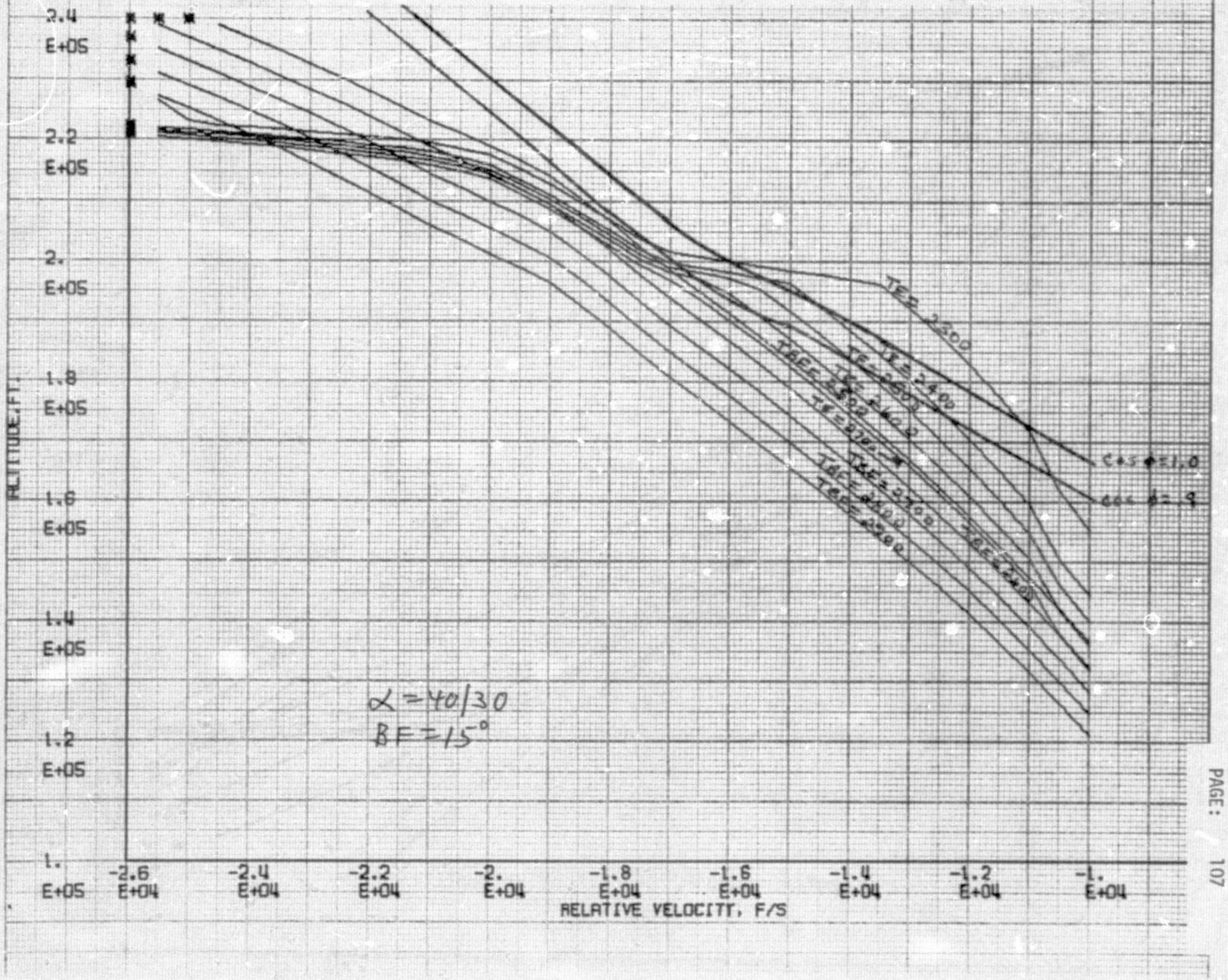

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FIGURE 101 ALTITUDE VS. VELOCITY CORRIDOR

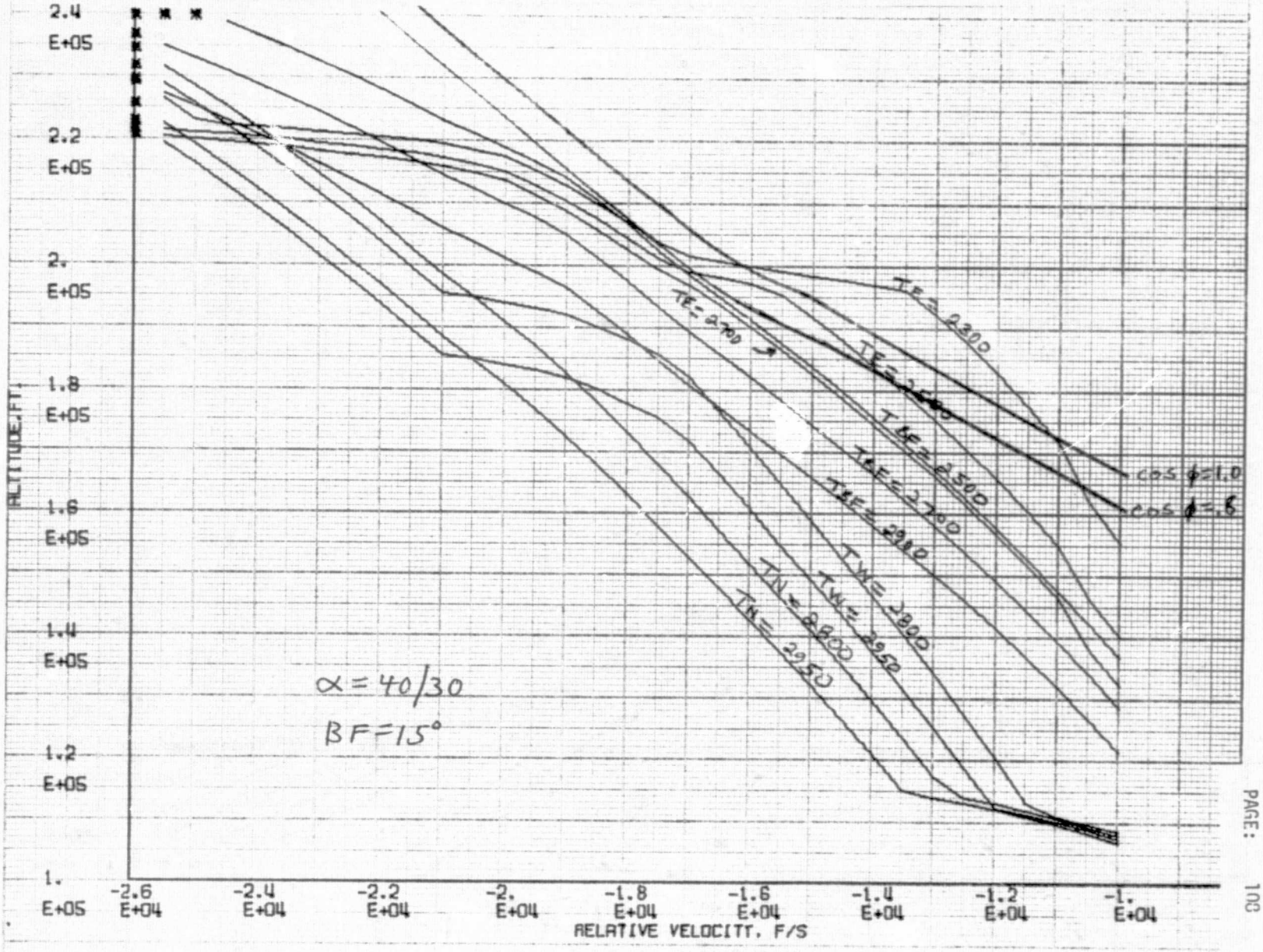

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FIGURE 102 ALTITUDE VS. VELOCITY CORRIDOR

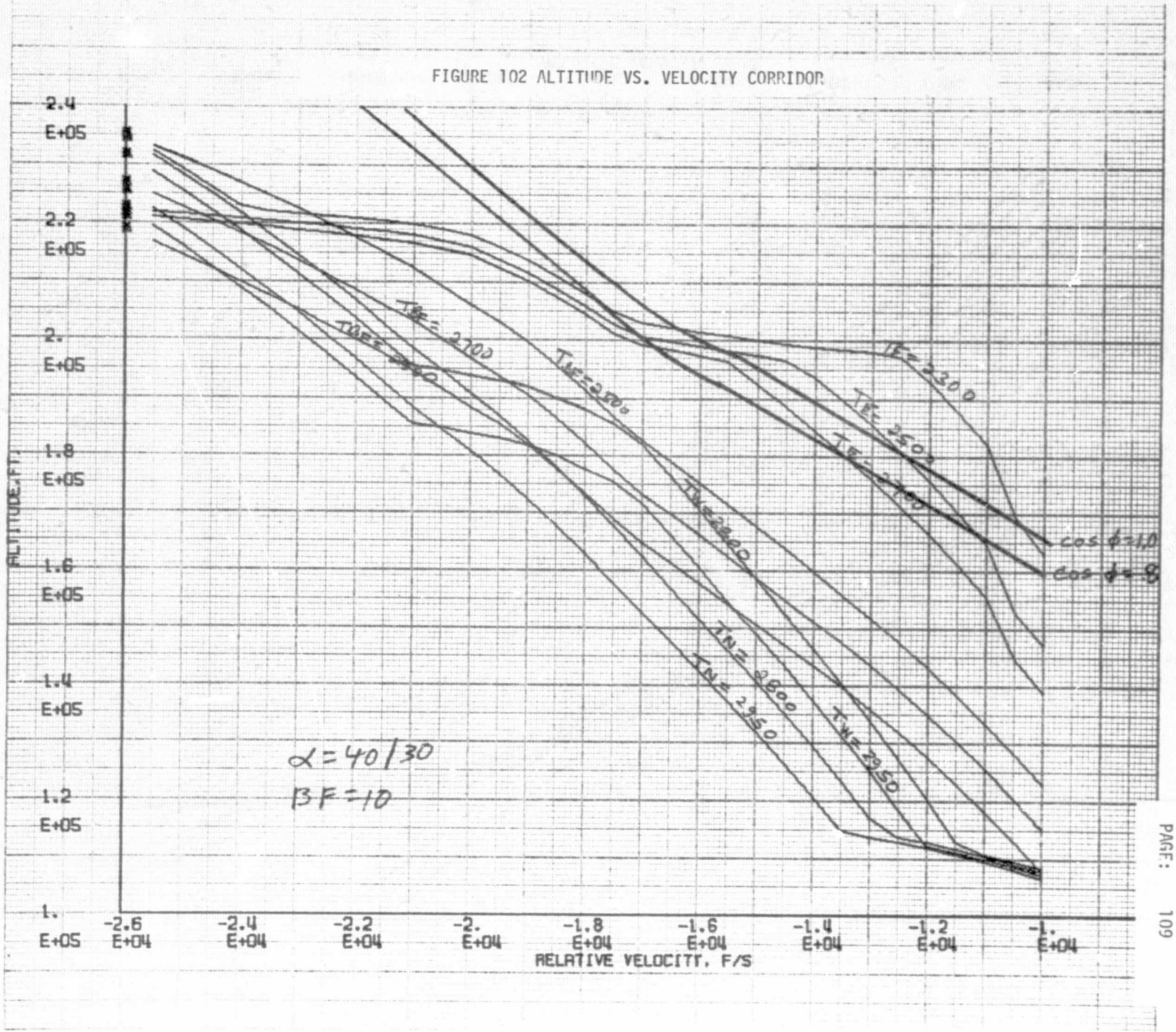

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FIGURE 10? ALTITUDE VS. VELOCITY CORRIDOR

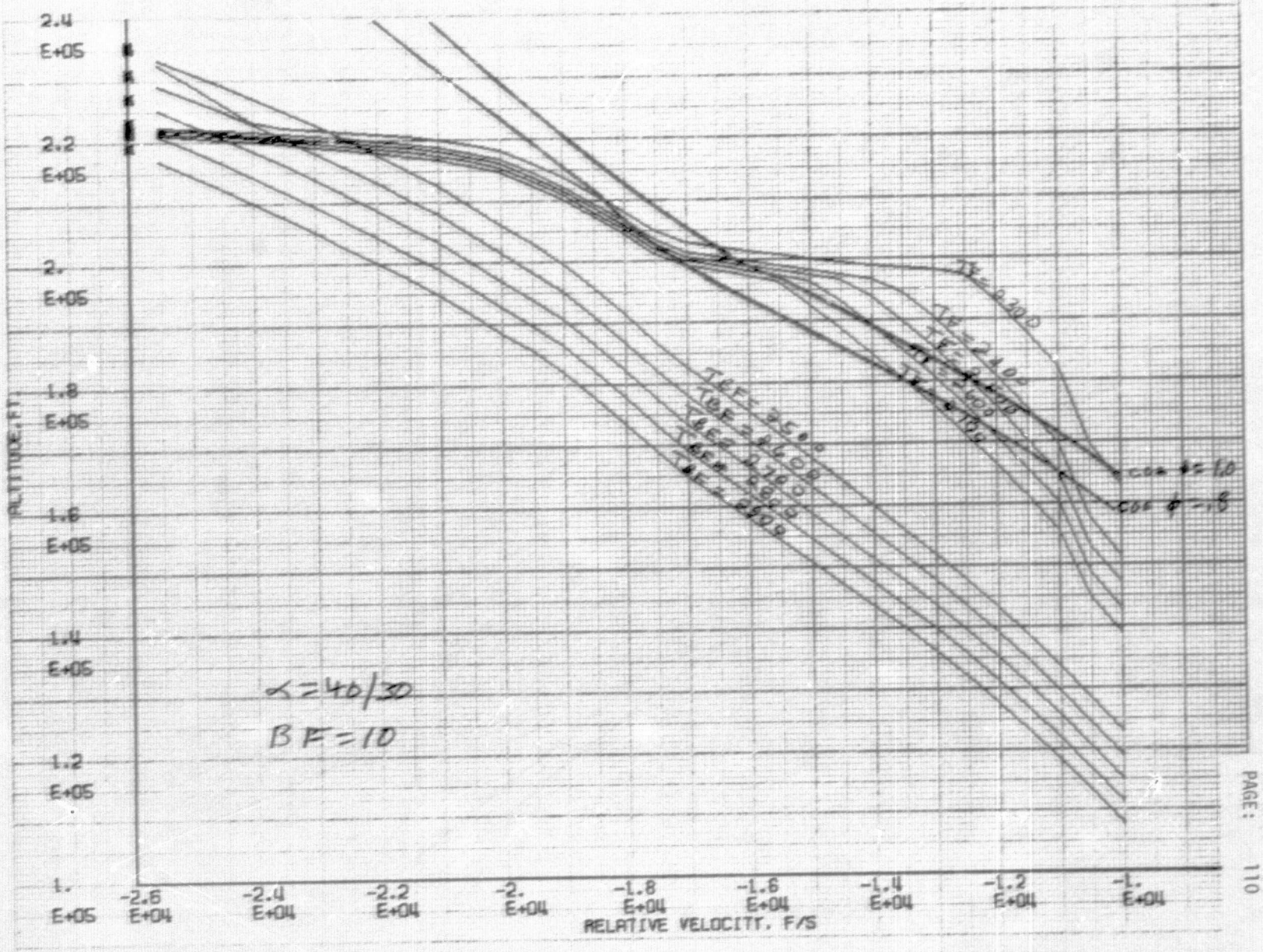

FIGURE 104 ALTITUDE VS. VELOCITY CORRIDOR

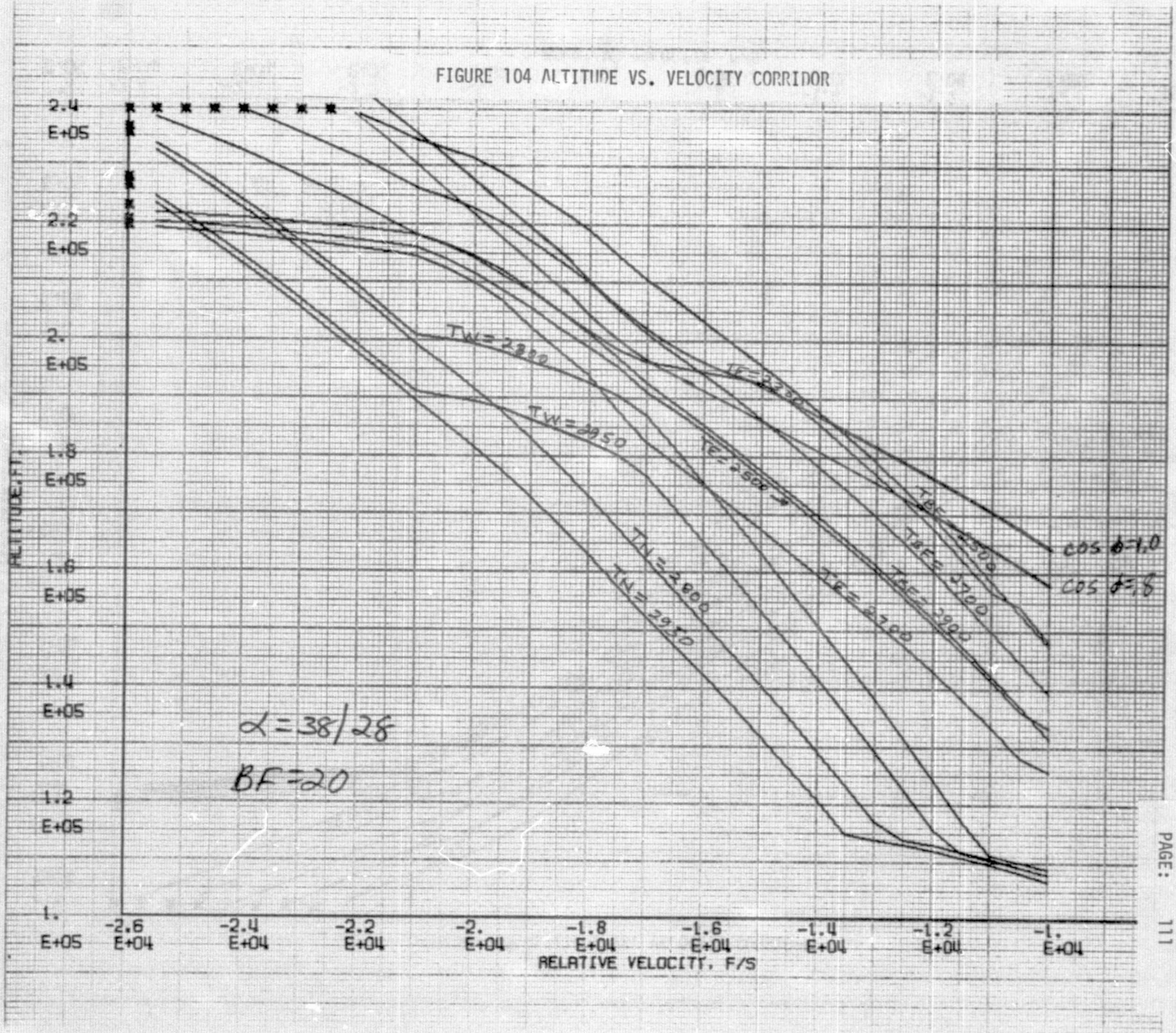

FIGURE 105 ALTITUDE VS. VELOCITY CORRIDOR

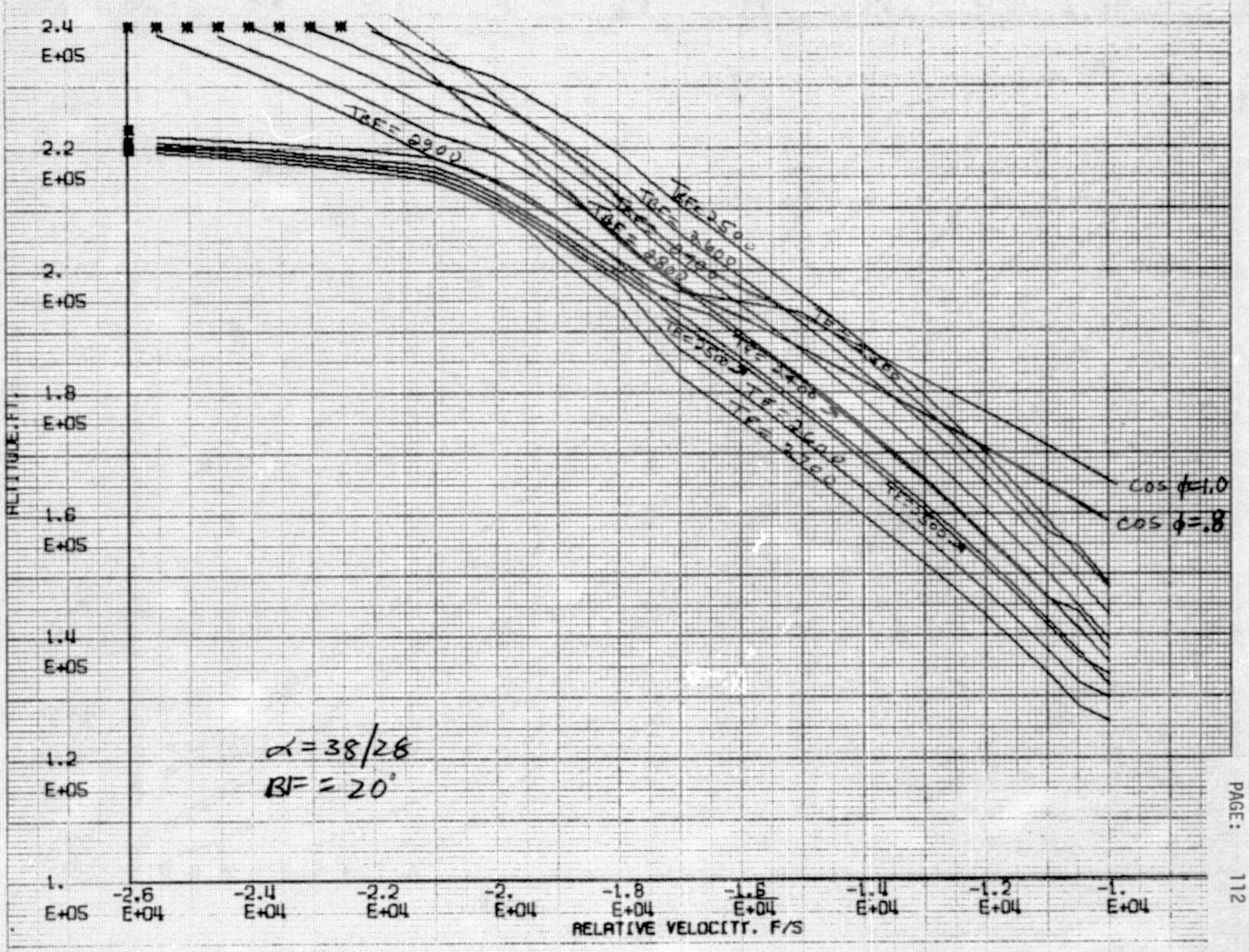

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FIGURE 106 ALTITUDE VS. VELOCITY CORRIDOR

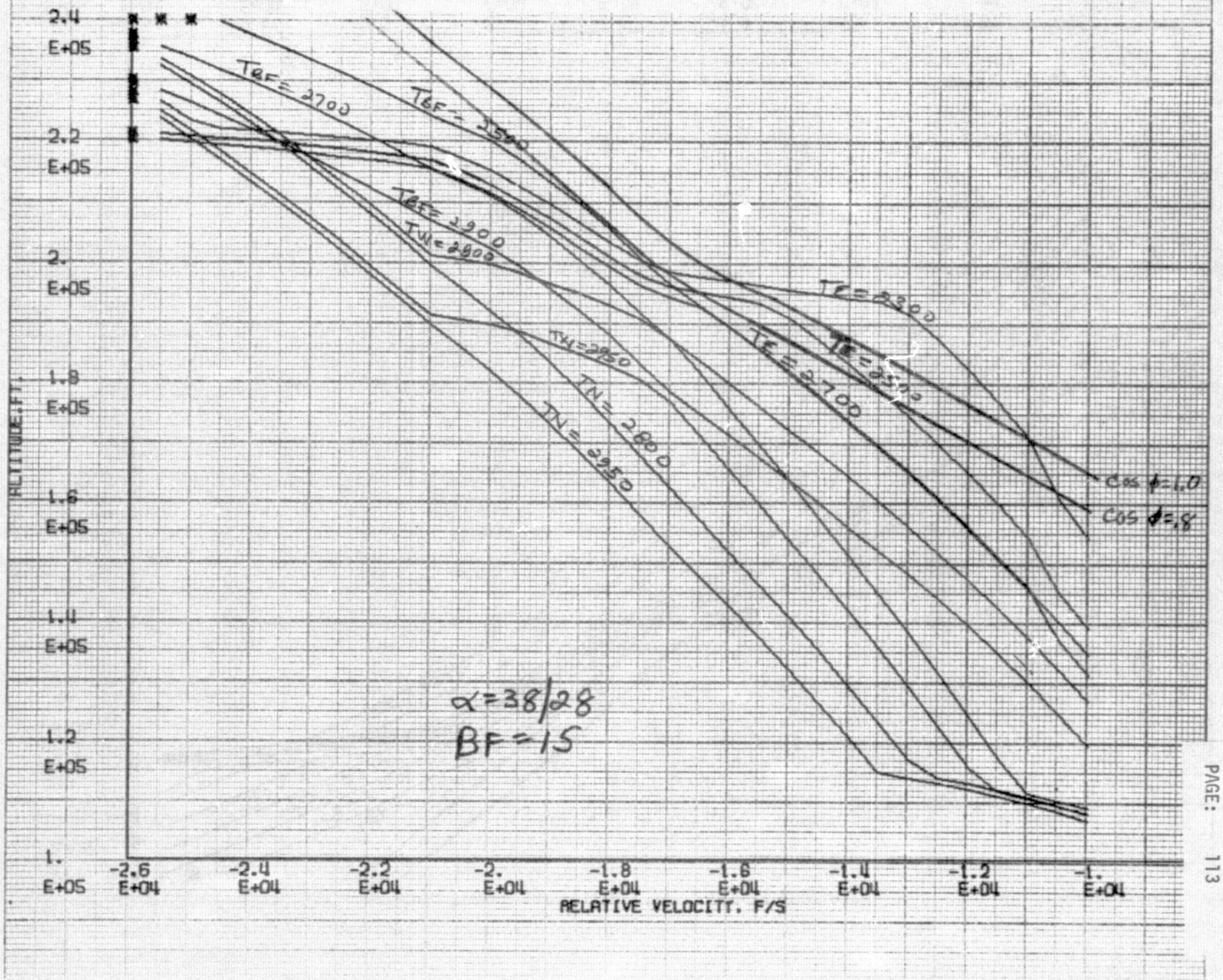

FIGURE 107 ALTITUDE VS. VELOCITY CORRIDOR

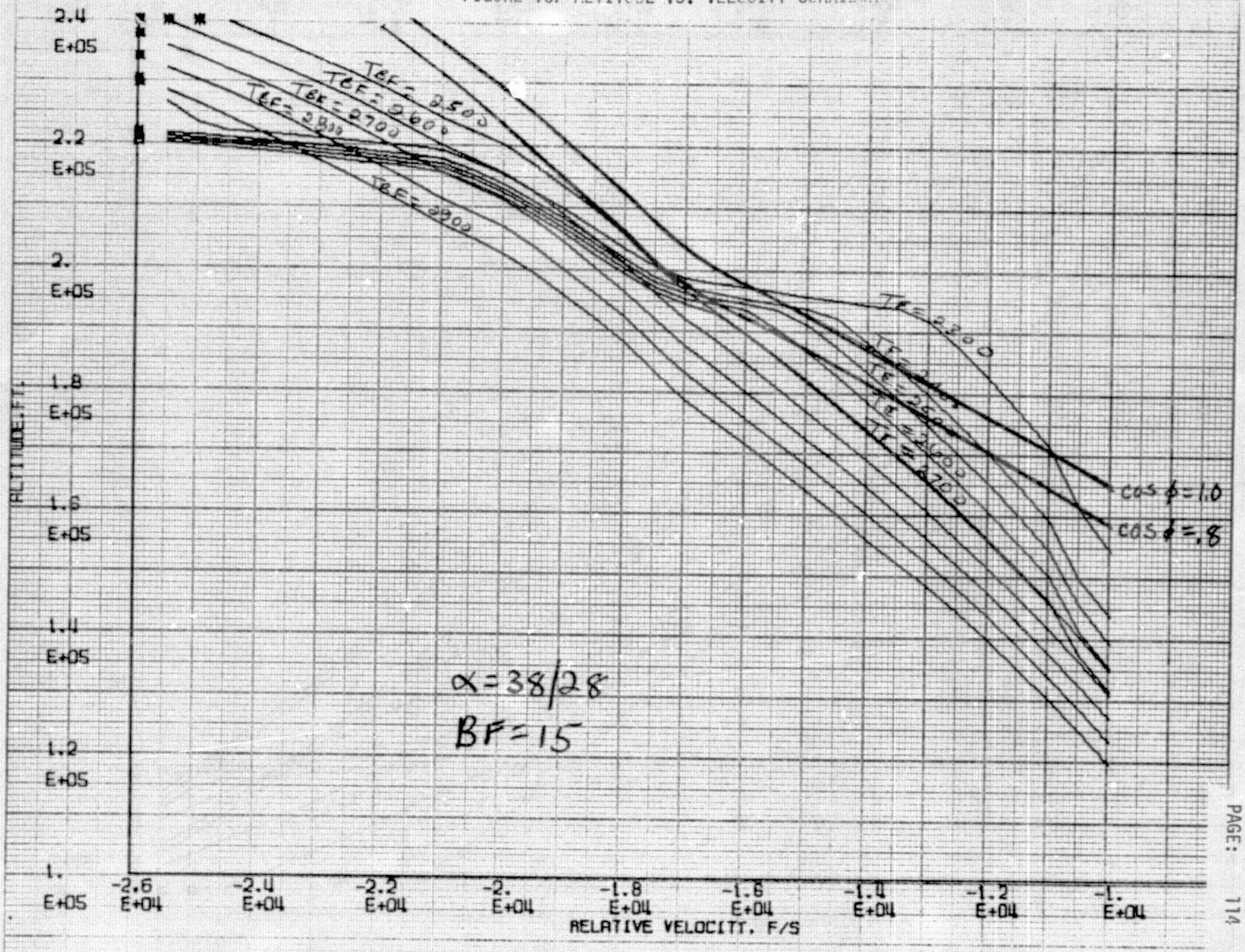

FIGURE 108 ALTITUDE VS. VELOCITY CORRIDOR

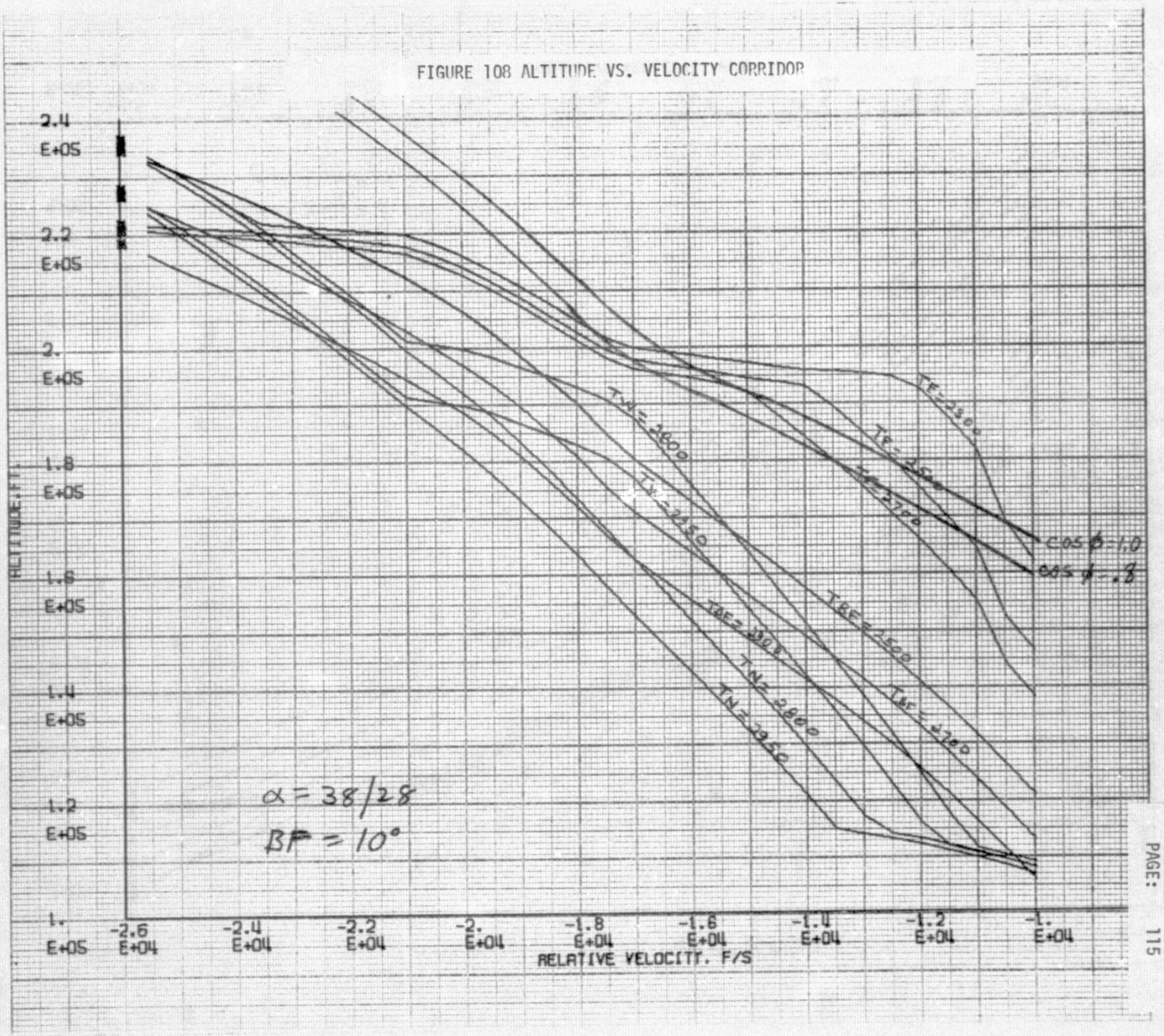

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FIGURE 109 ALTITUDE VS. VELOCITY CORRIDOR

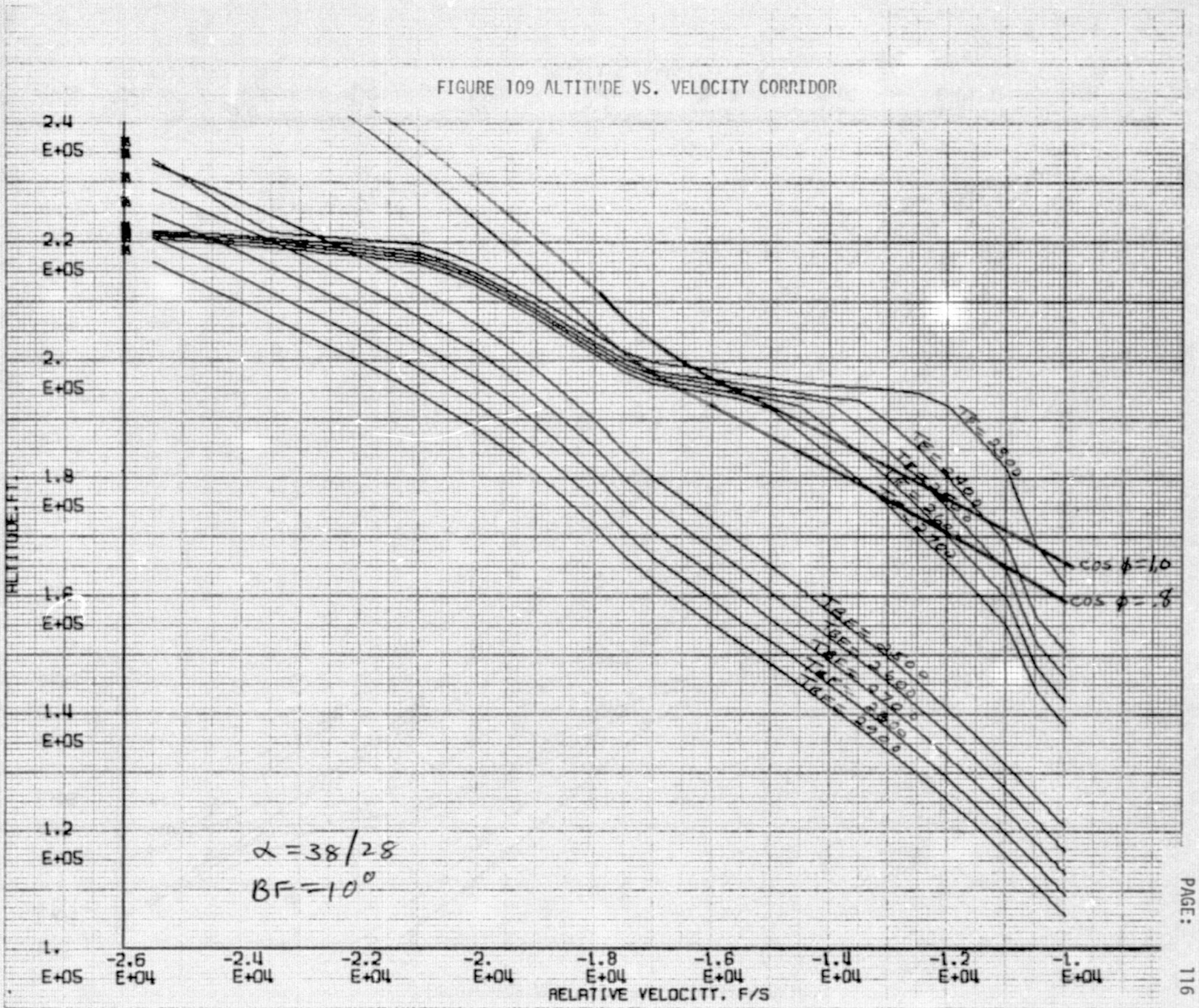

FIGURE 110 ALTITUDE VS. VELOCITY CORRIDOR

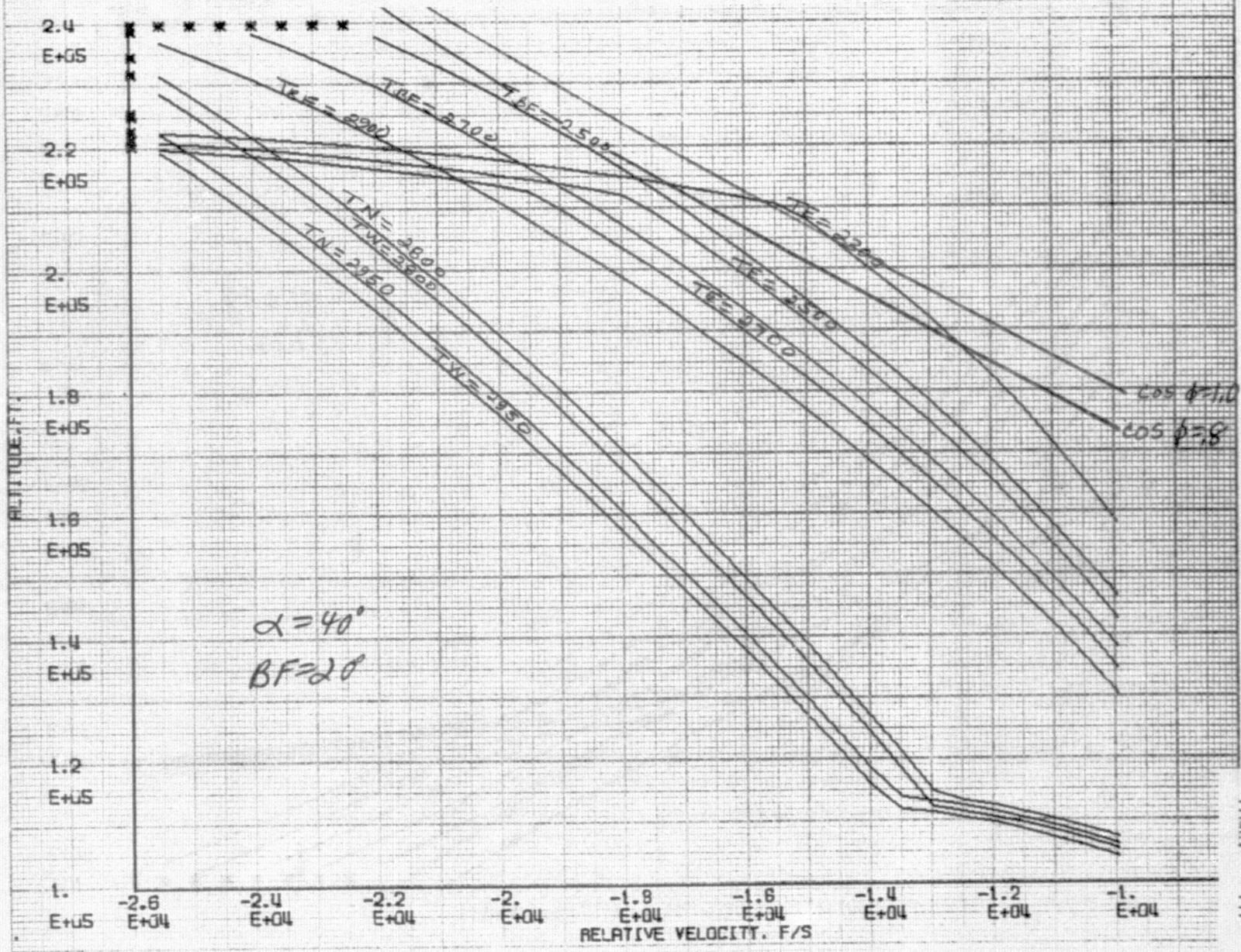

FIGURE 111 ALTITUDE VS. VELOCITY CORRIDOR

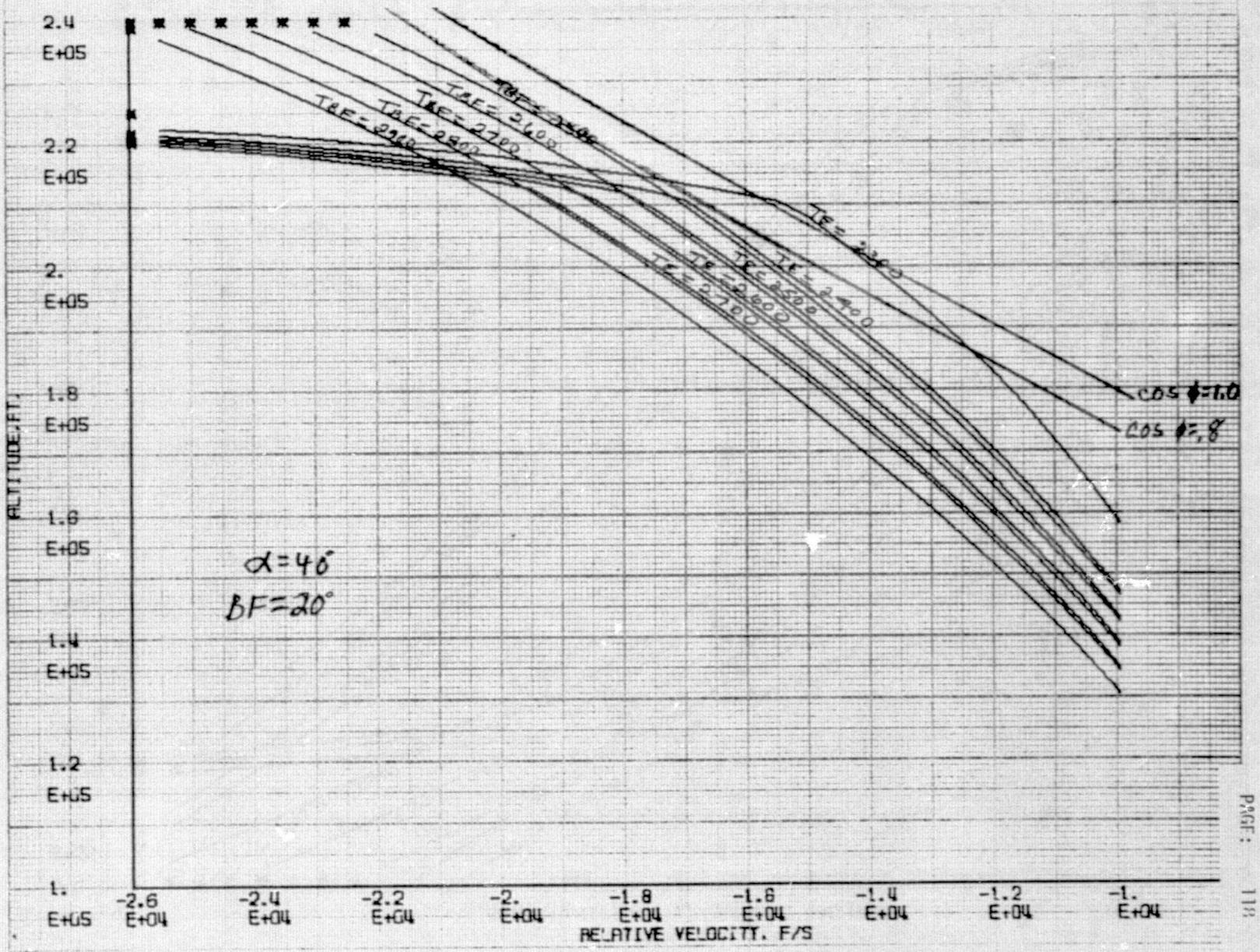

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FIGURE 112 ALTITUDE VS. VELOCITY CORRIDOR

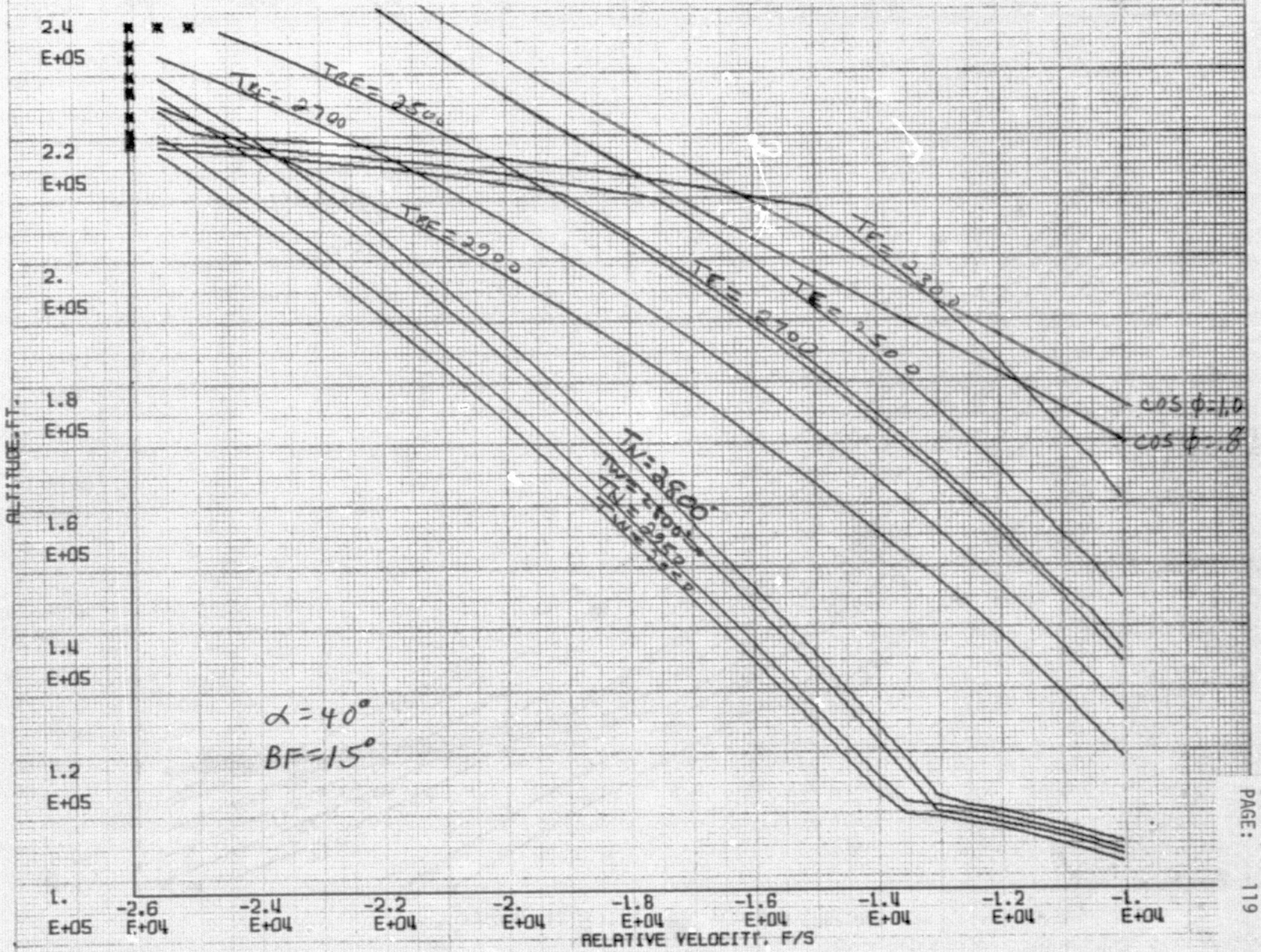

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FIGURE 113 ALTITUDE VS. VELOCITY CORRIDOR

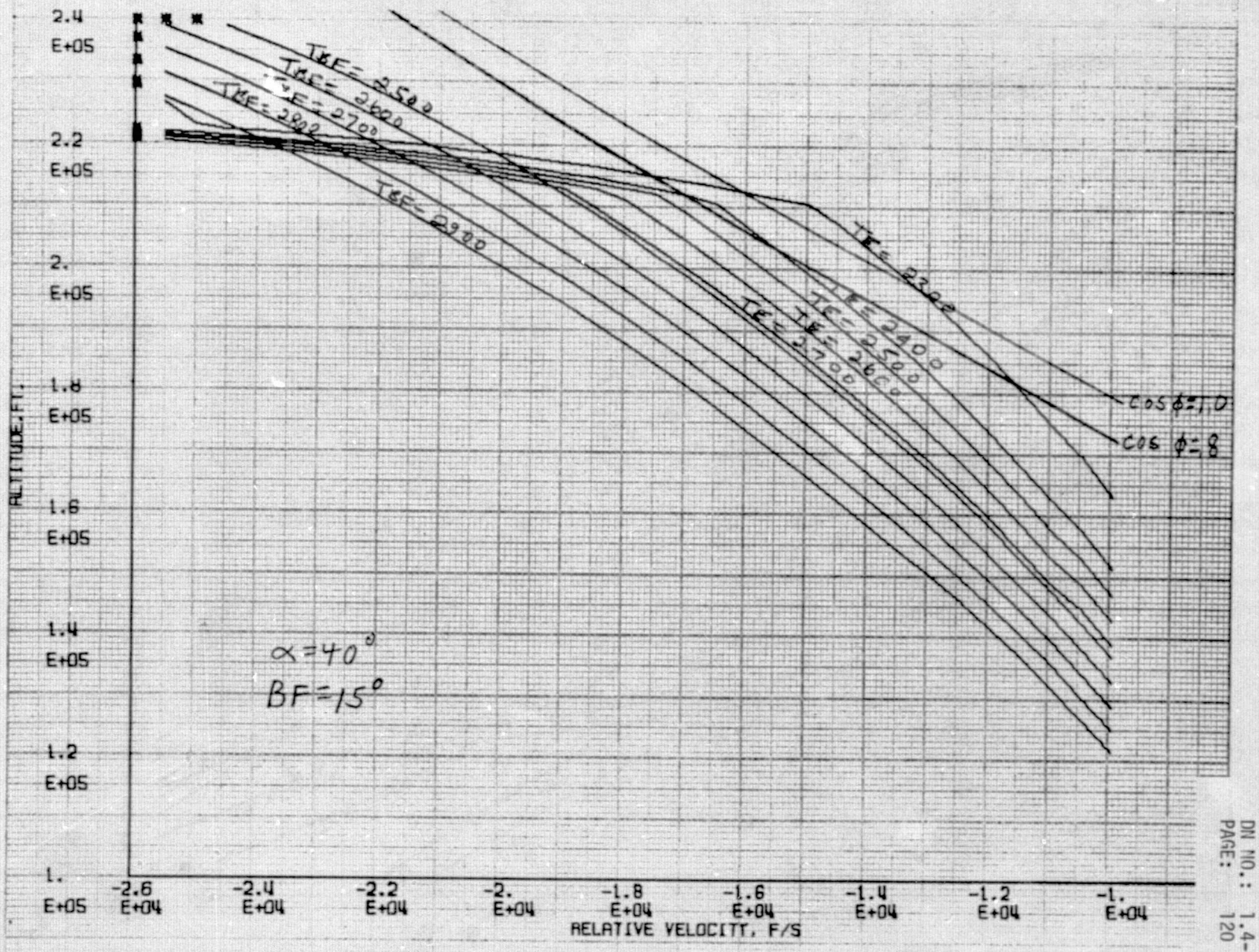

FIGURE 114 ALTITUDE VS. VELOCITY CORRIDOR

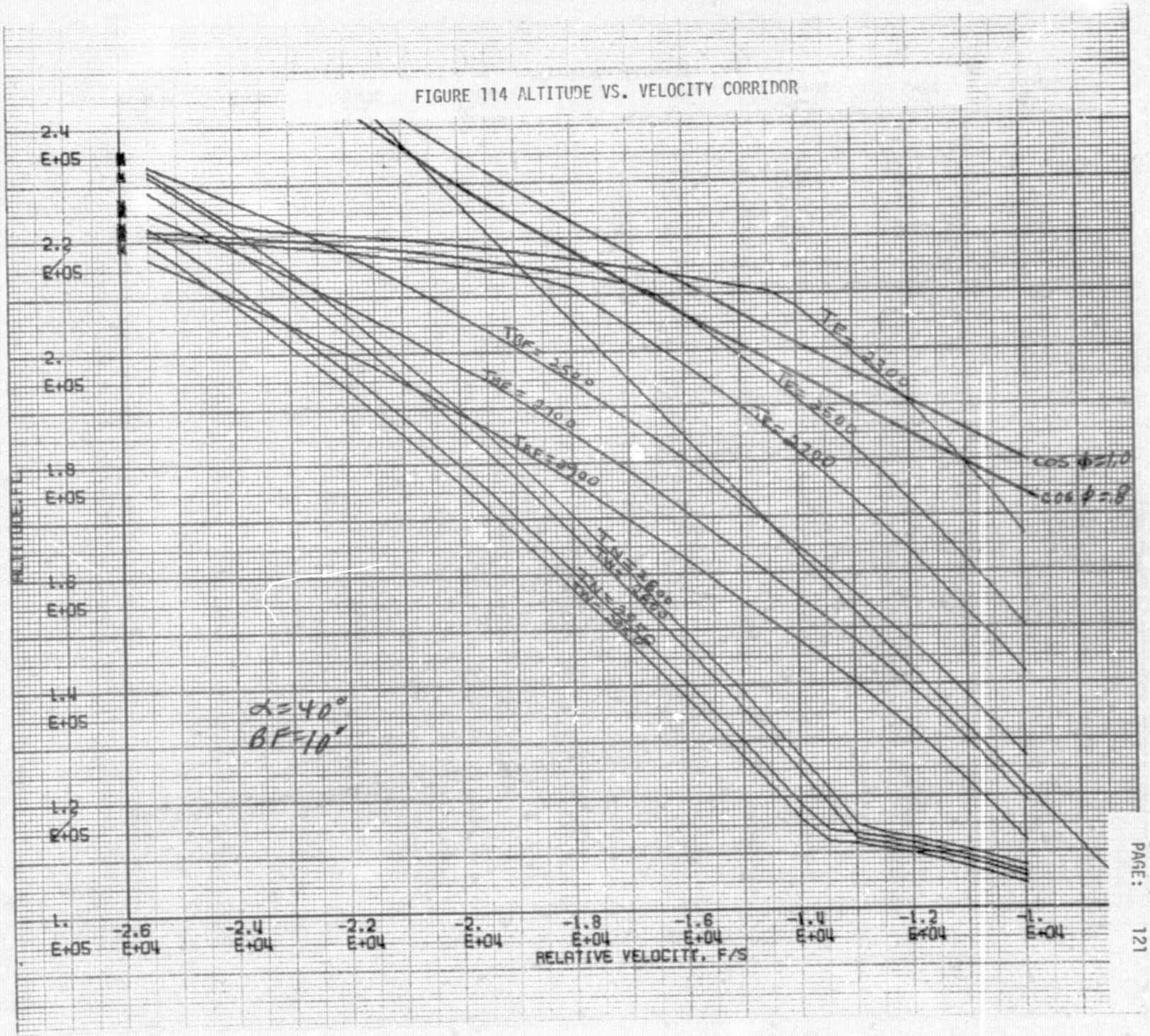

FIGURE 115 ALTITUDE VS. VELOCITY CORRIDOR

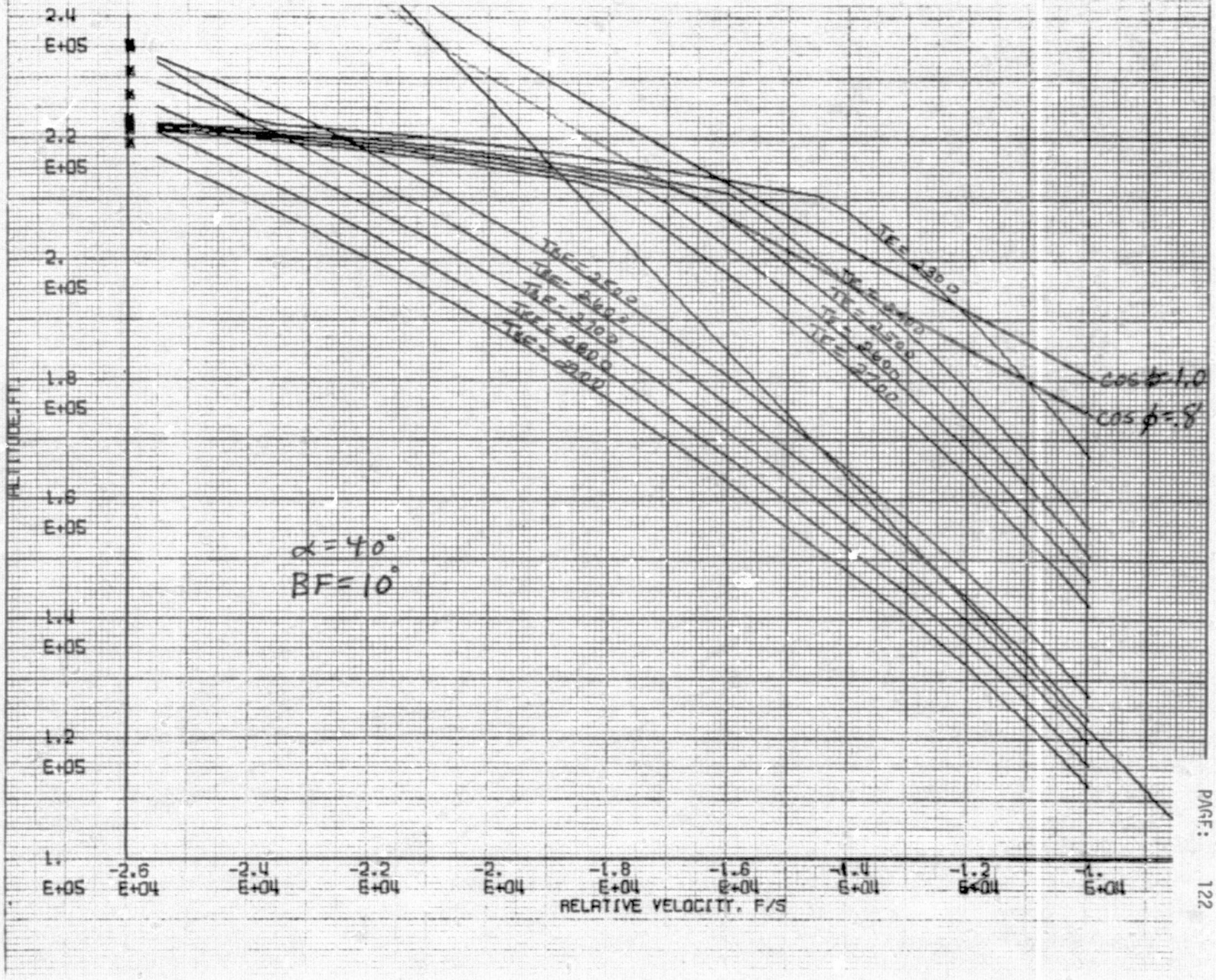

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FIGURE 116 ALTITUDE VS. VELOCITY CORRIDOR

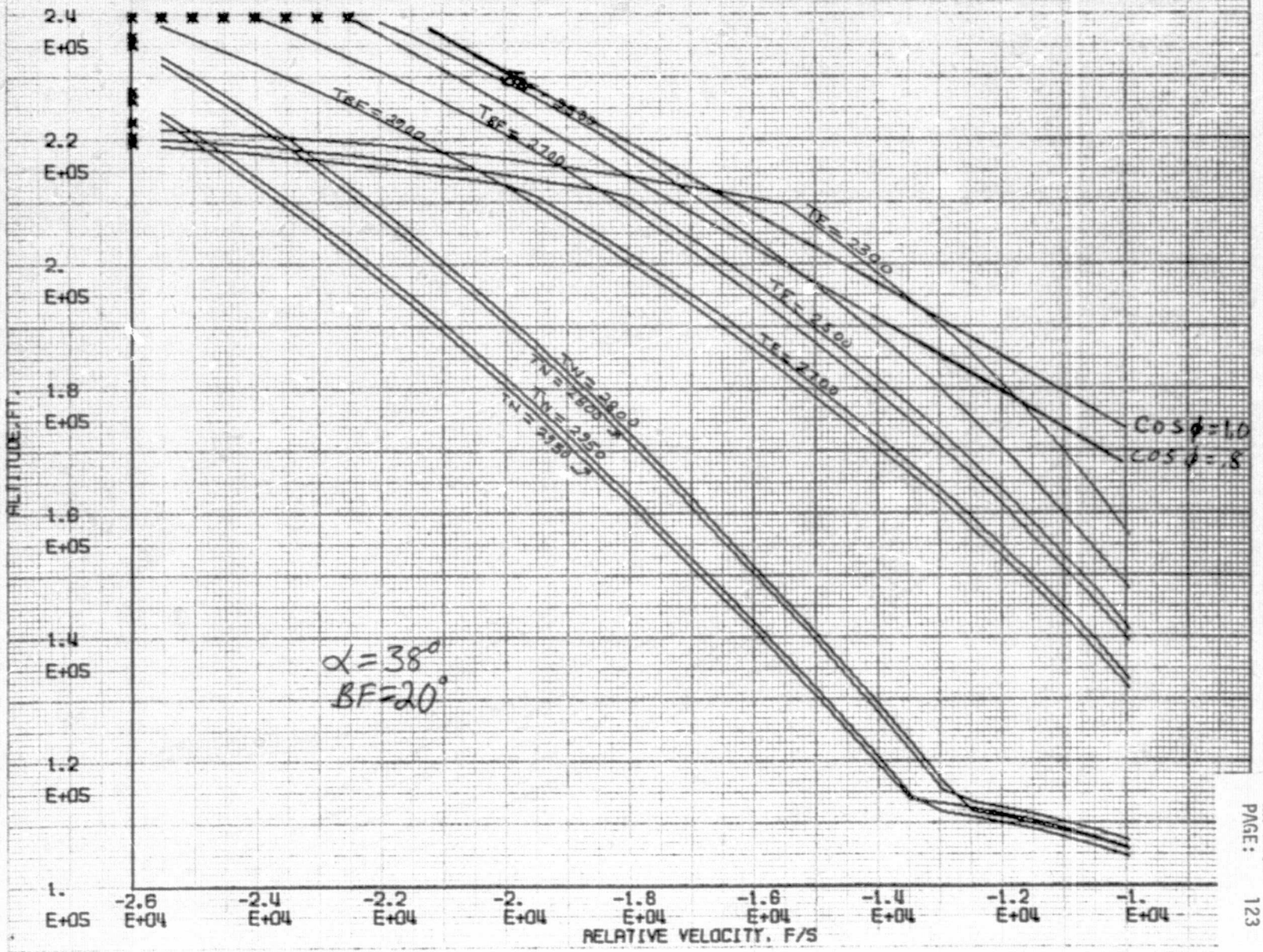

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FIGURE 117 ALTITUDE VS. VELOCITY CORRIDOR

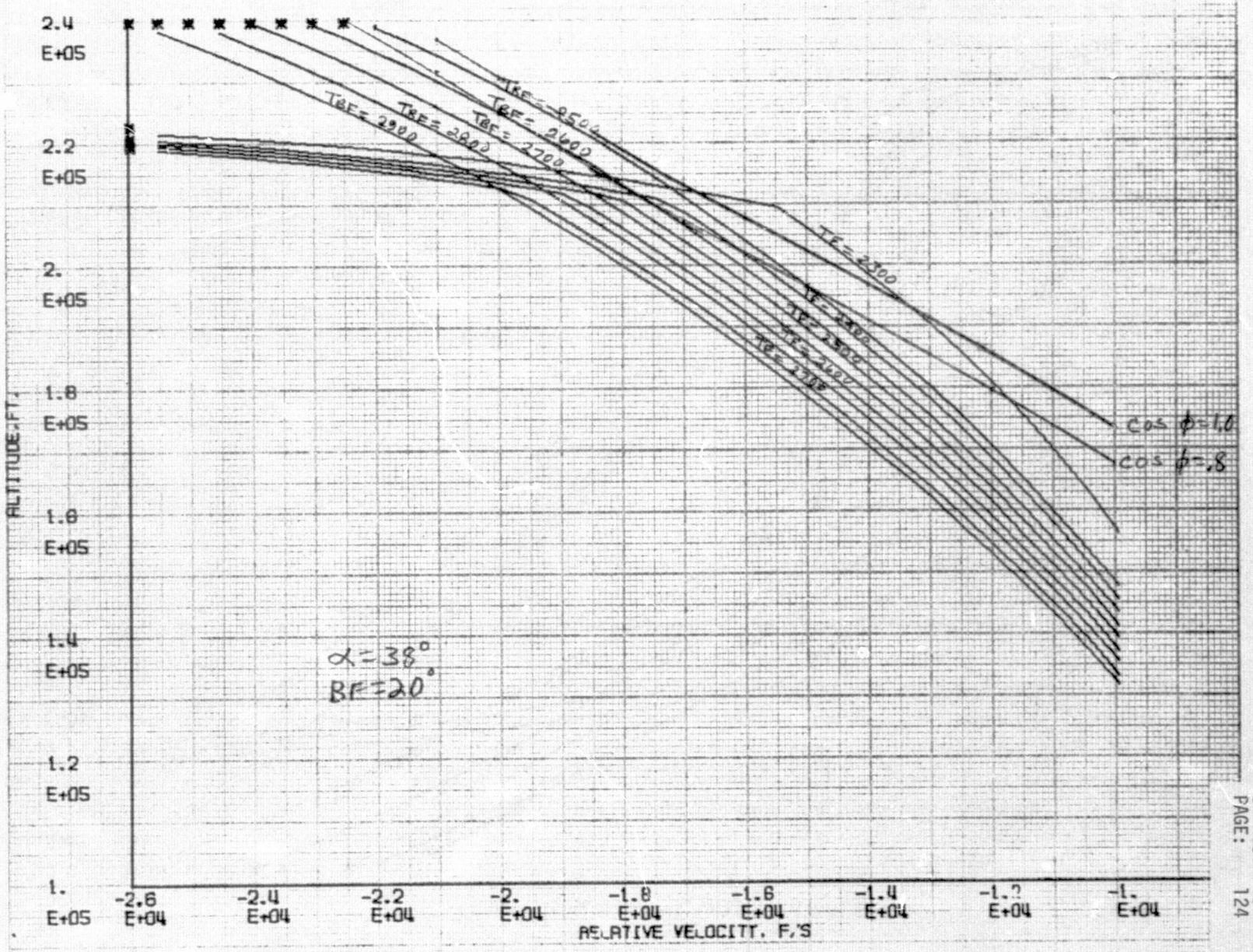

FIGURE 118 ALTITUDE VS. VELOCITY CORRIDOR

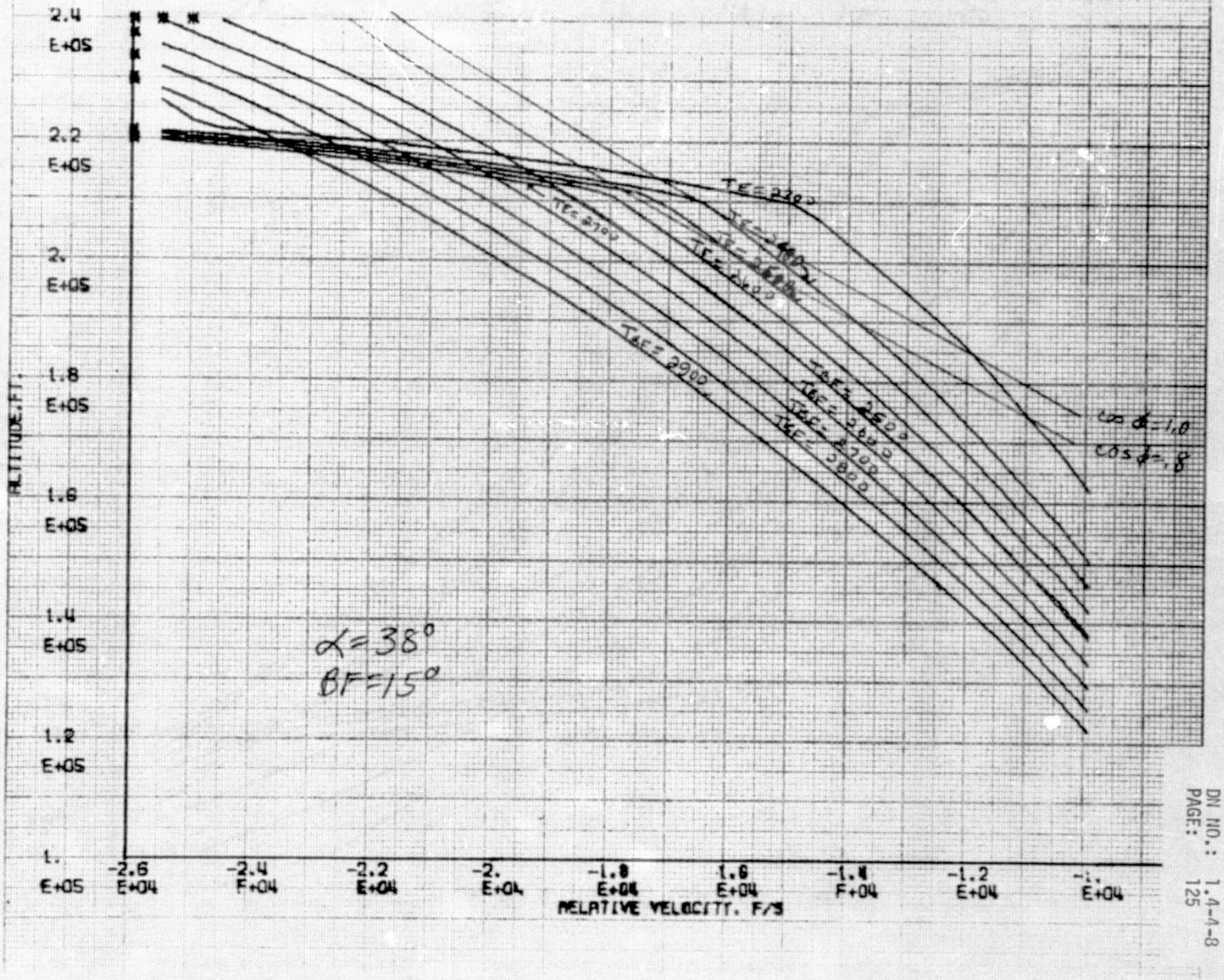

FIGURE 119 ALTITUDE VS. VELOCITY CORRIDOR

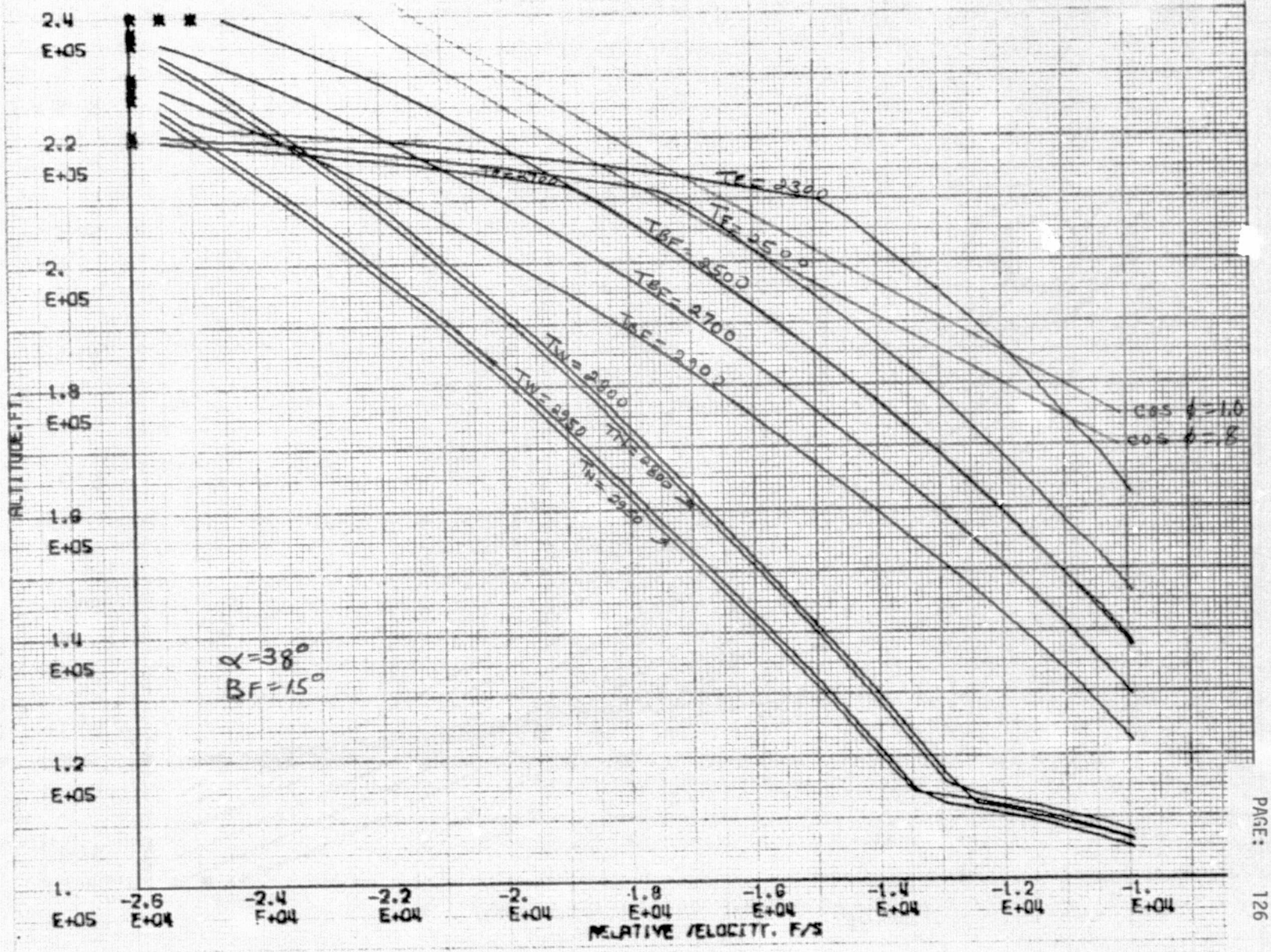

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FIGURE 120 ALTITUDE VS. VELOCITY CORRIDOR

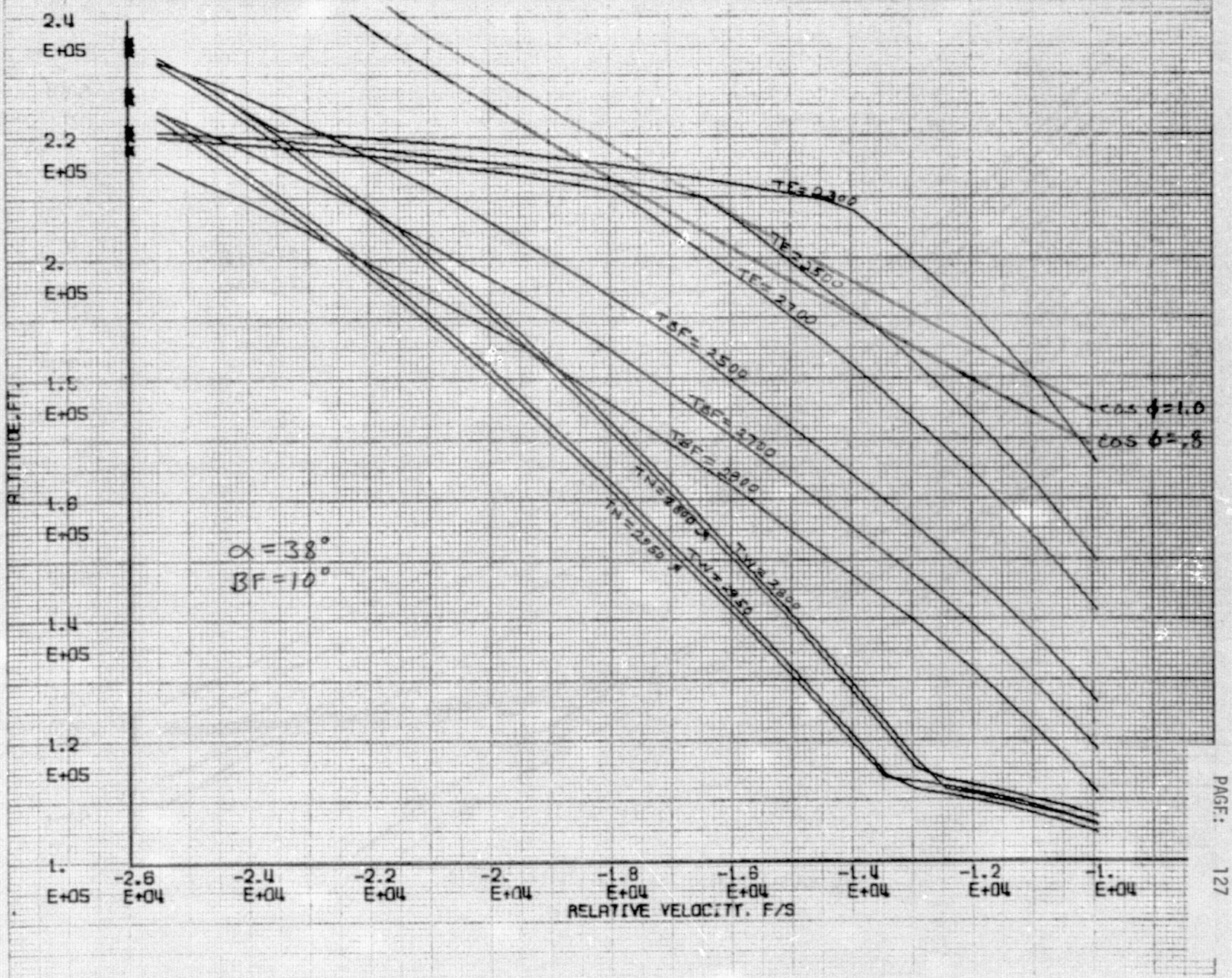

FIGURE 121 ALTITUDE VS. VELOCITY CORRIDOR

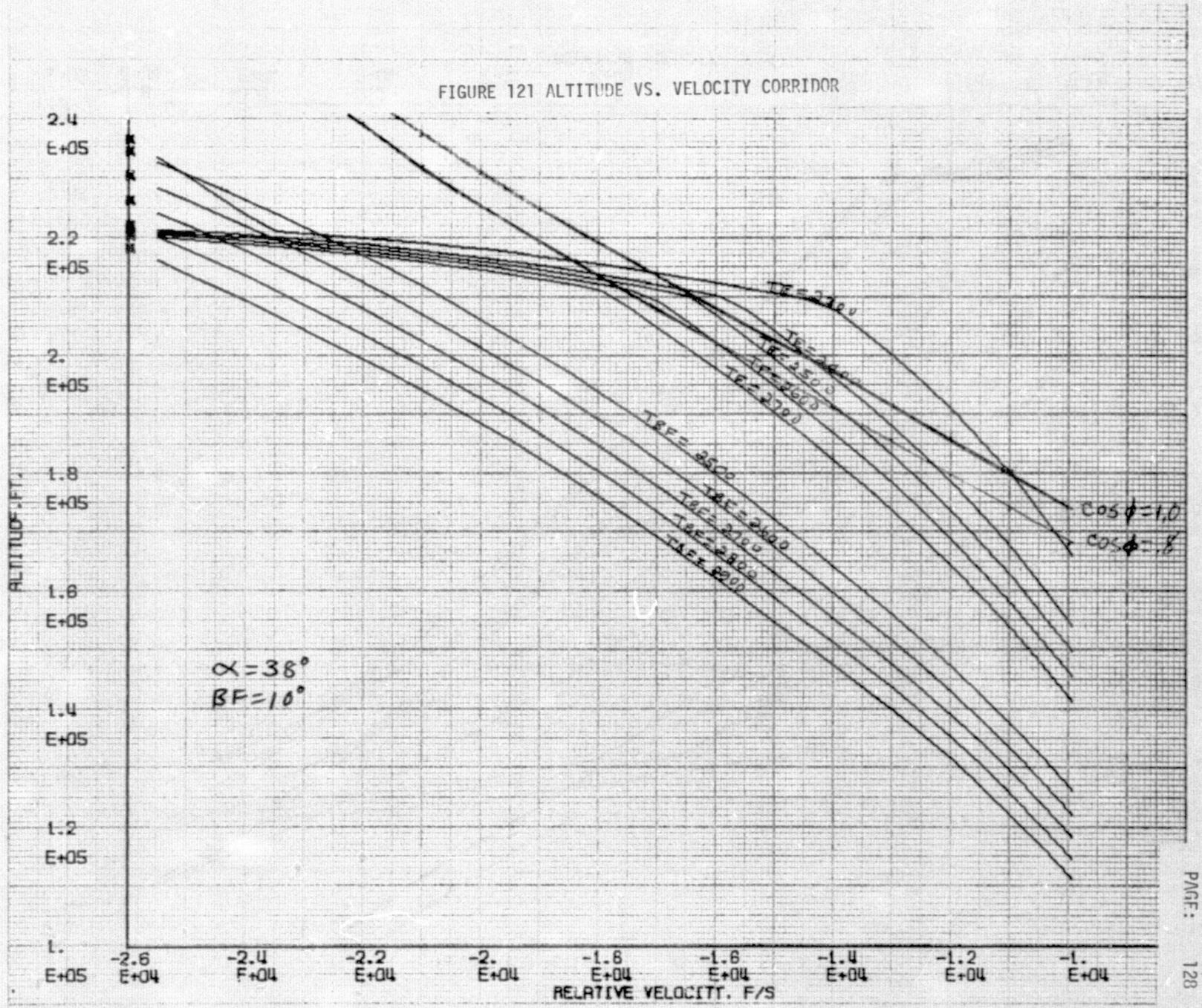

FIGURE 122 ALTITUDE VS. VELOCITY CORRIDOR

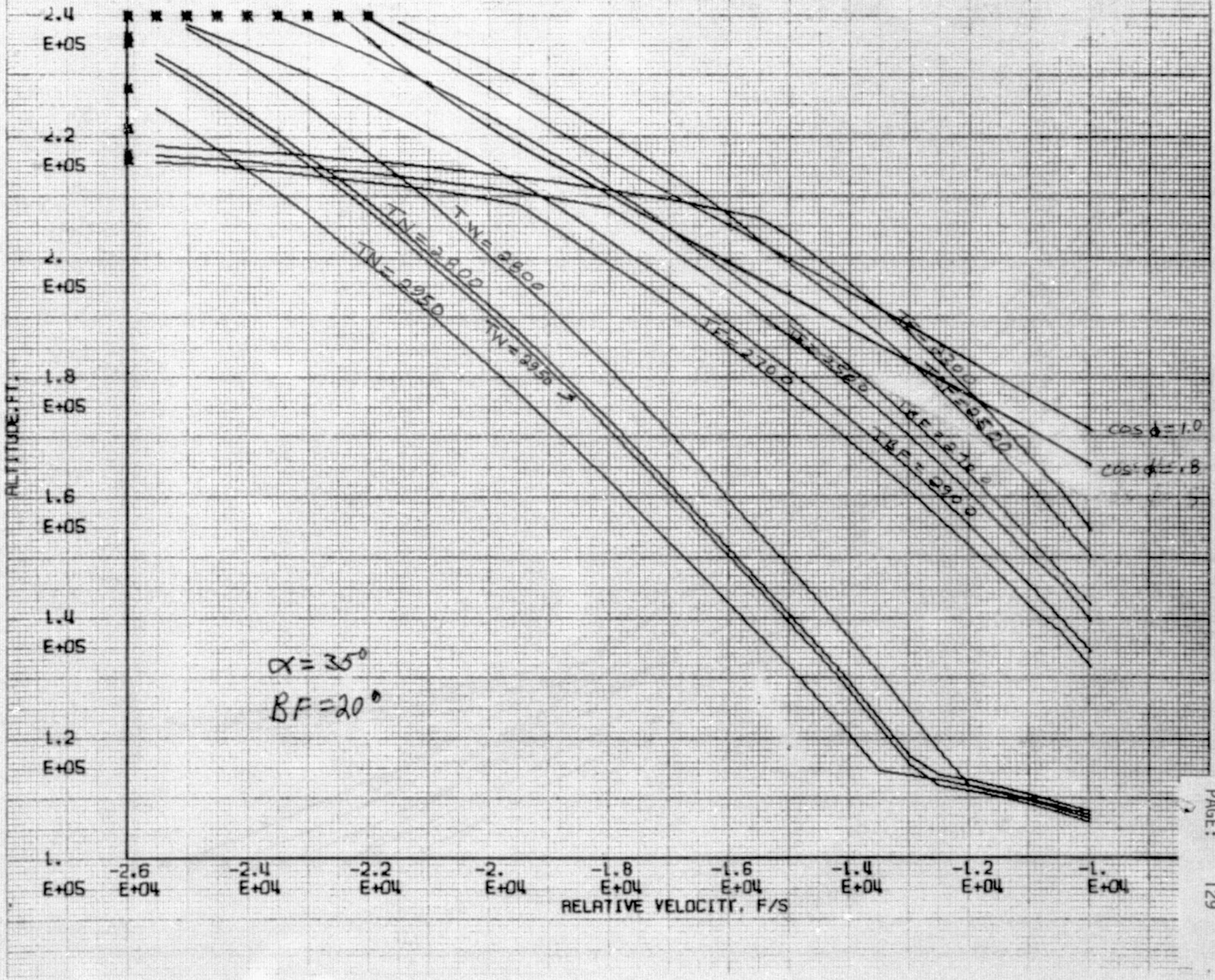

FIGURE 123 ALTITUDE VS. VELOCITY CORRIDOR

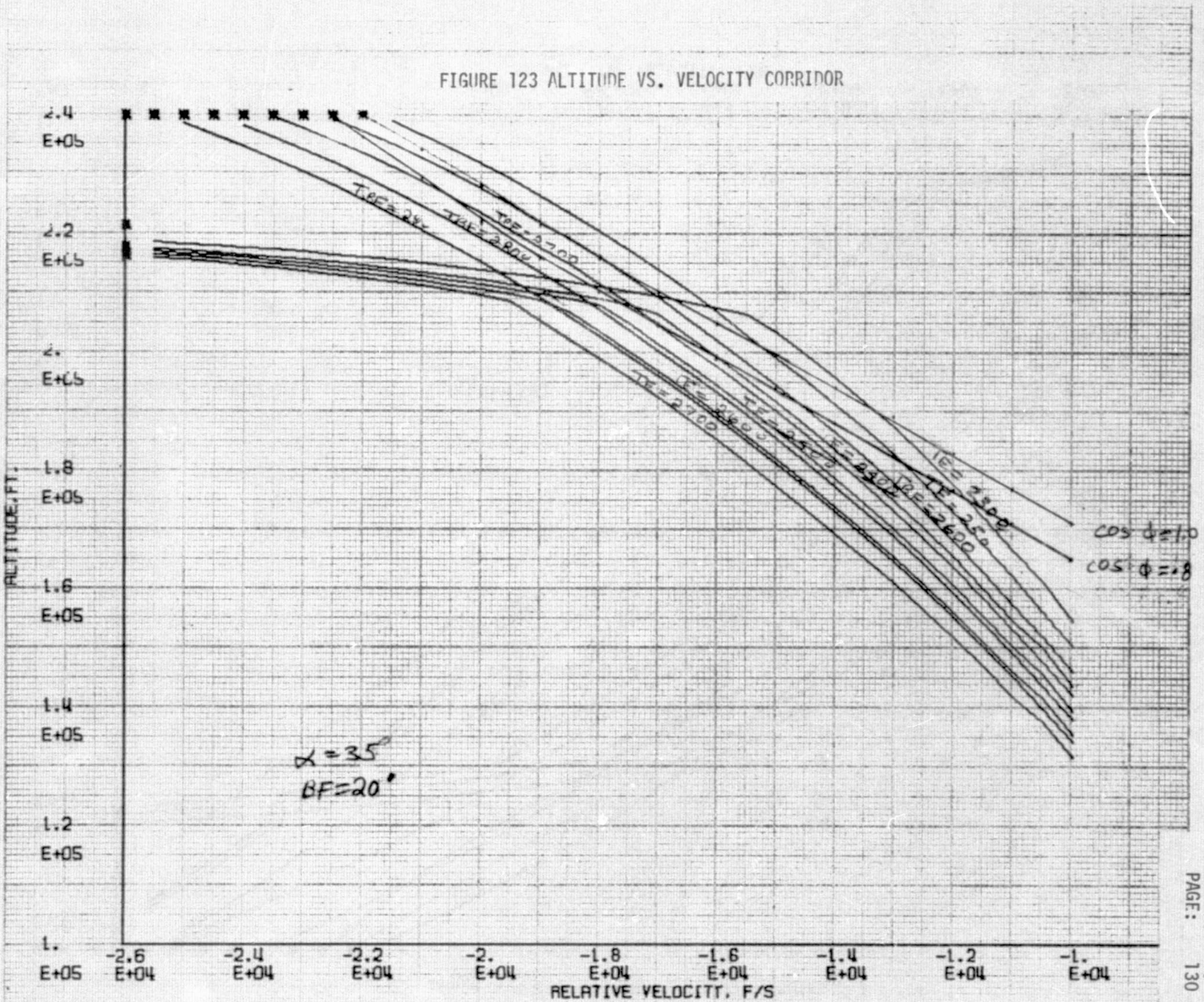

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FIGURE 124 ALTITUDE VS. VELOCITY CORRIDOR

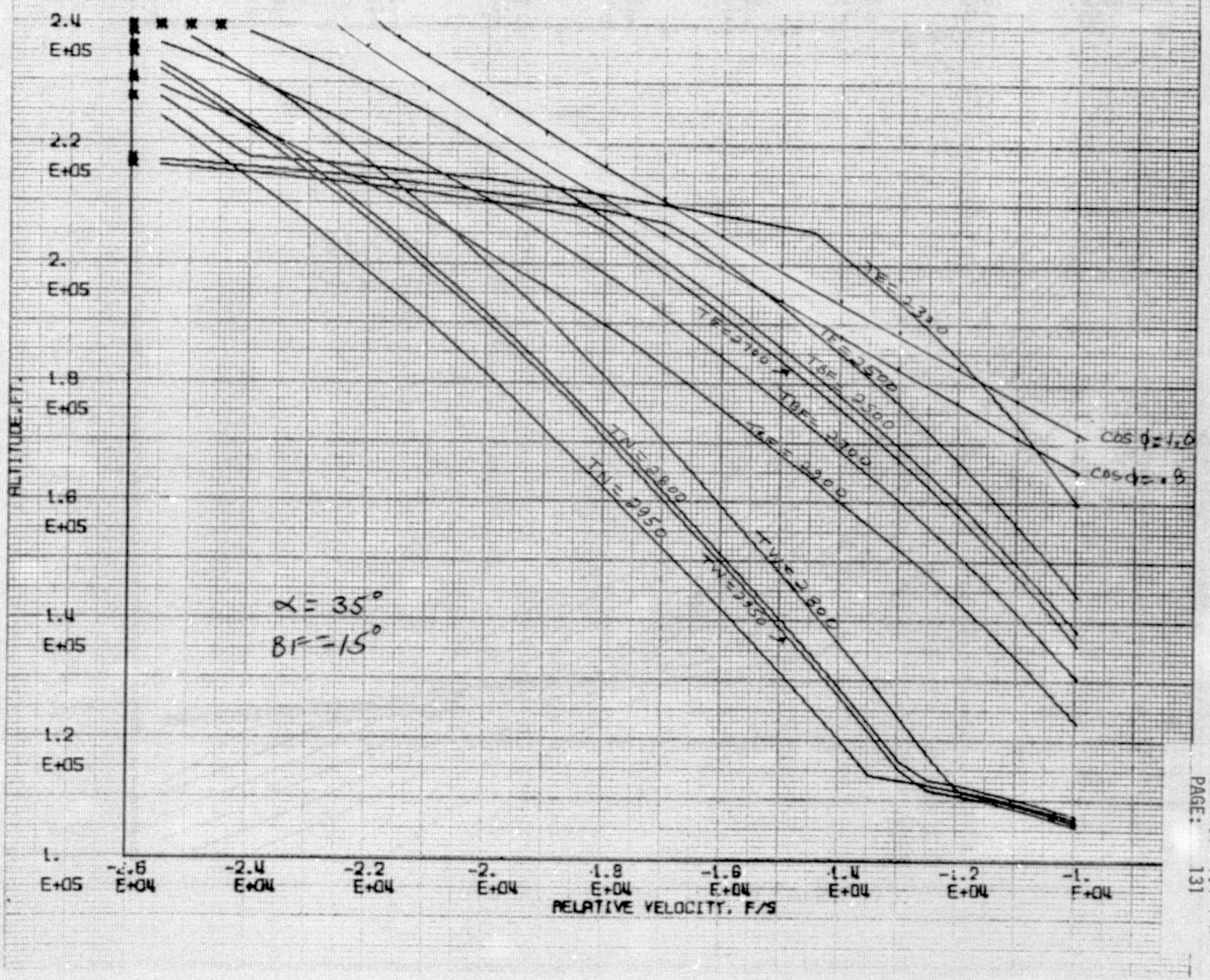

FIGURE 125 ALTITUDE VS. VELOCITY CORRIDOR

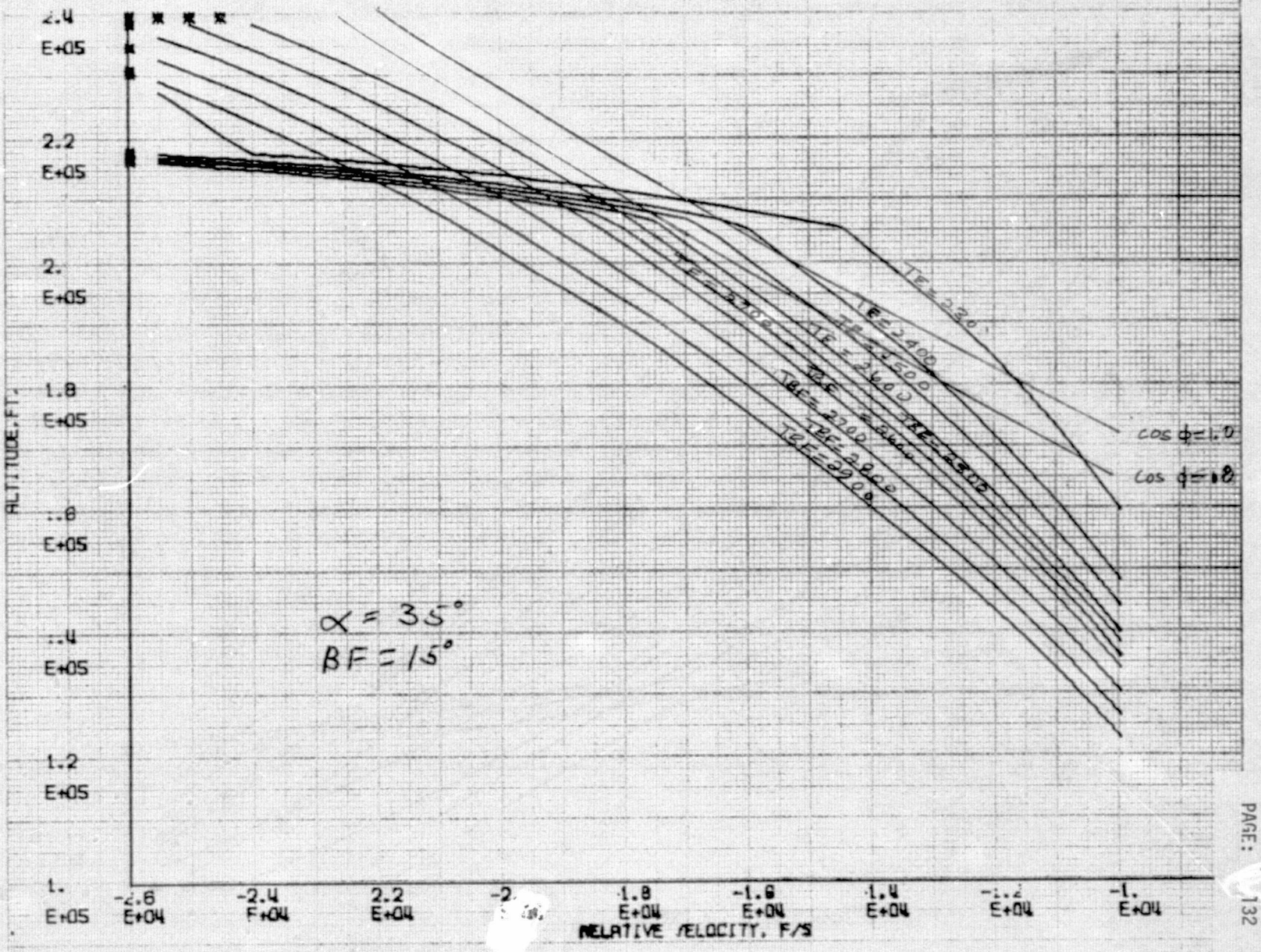

FIGURE 126 ALTITUDE VS. VELOCITY CORRIDOR

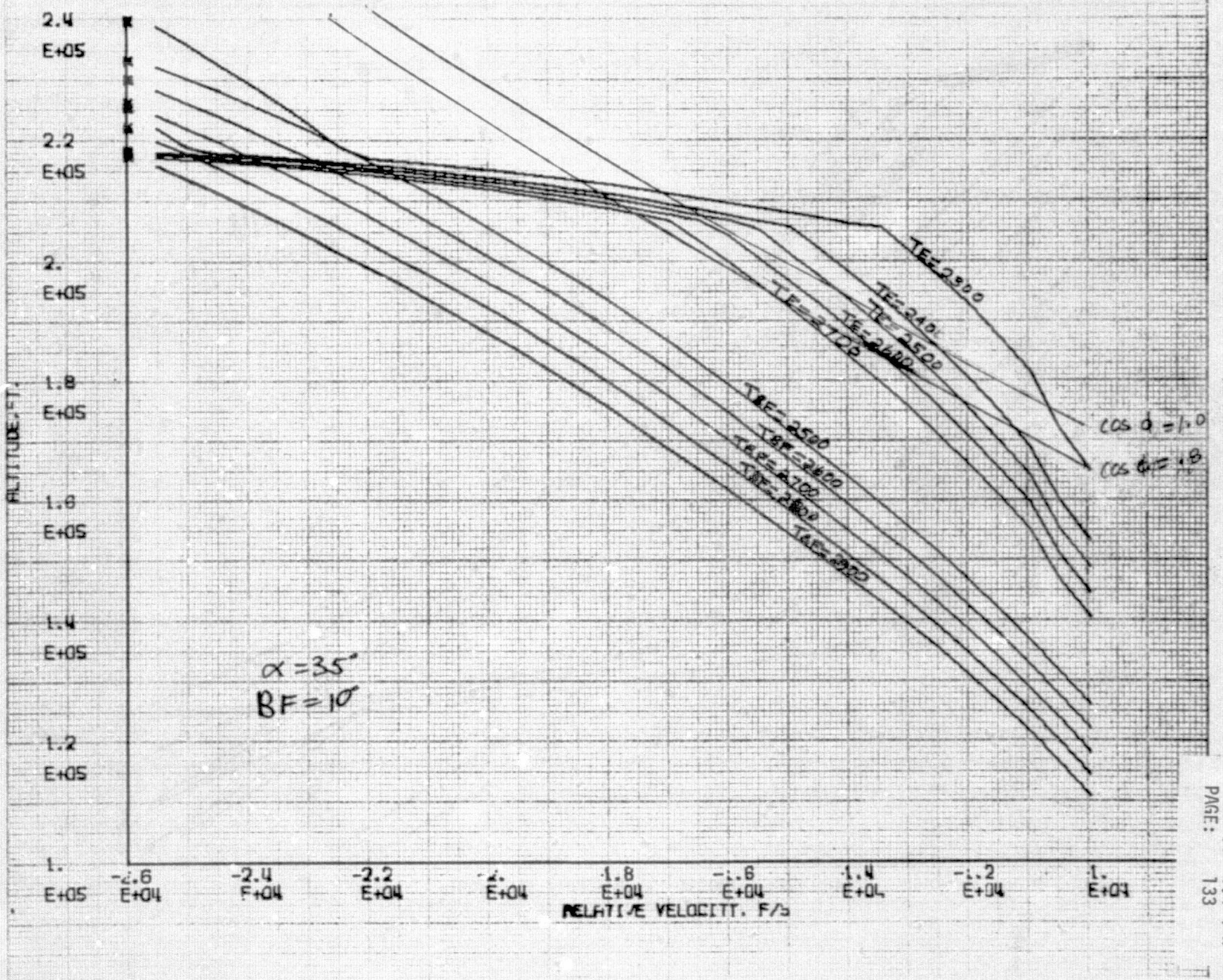

FIGURE 127 ALTITUDE VS. VELOCITY CORRIDOR

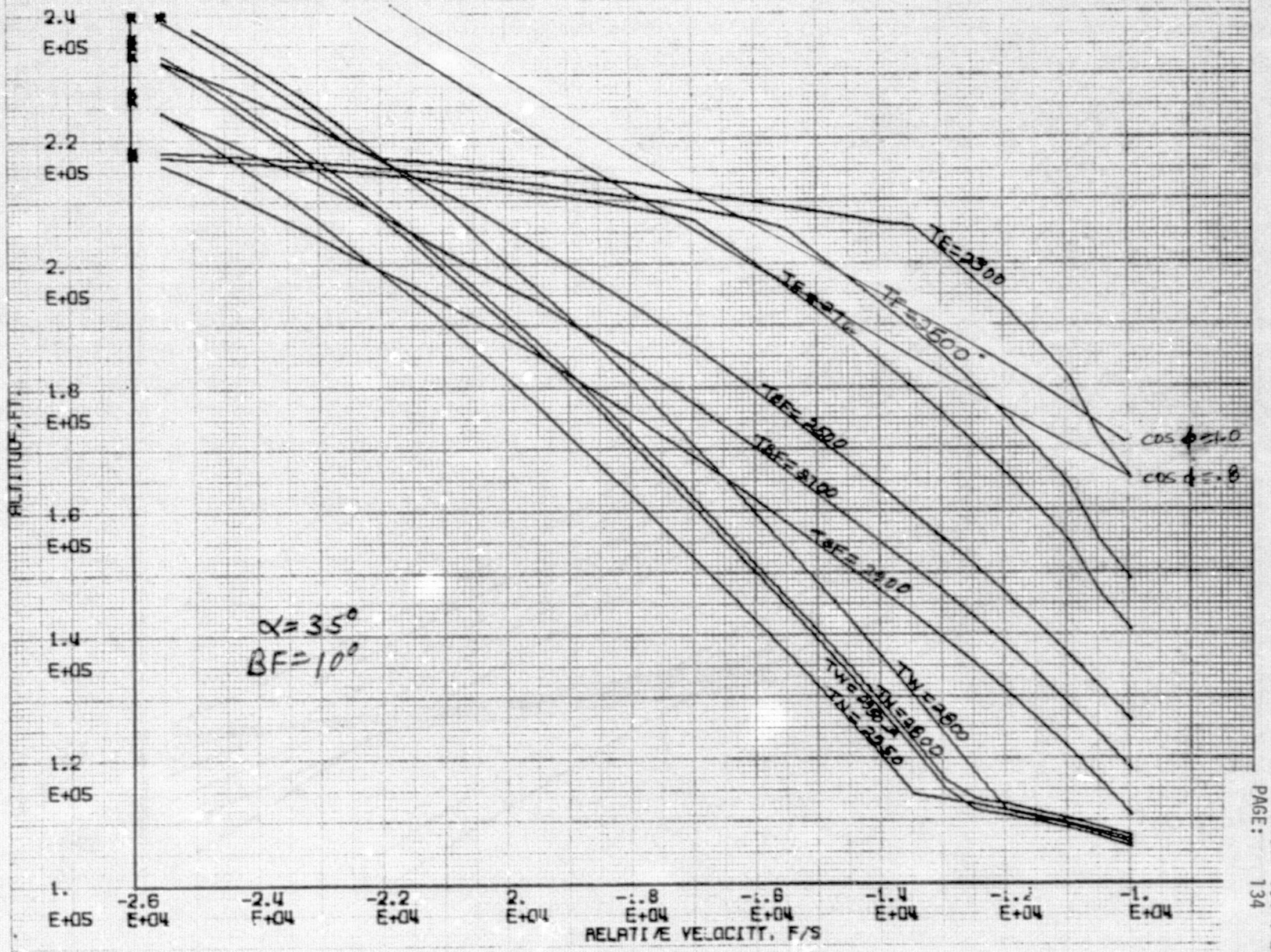

FIGURE 128 ALTITUDE VS. VELOCITY CORRIDOR

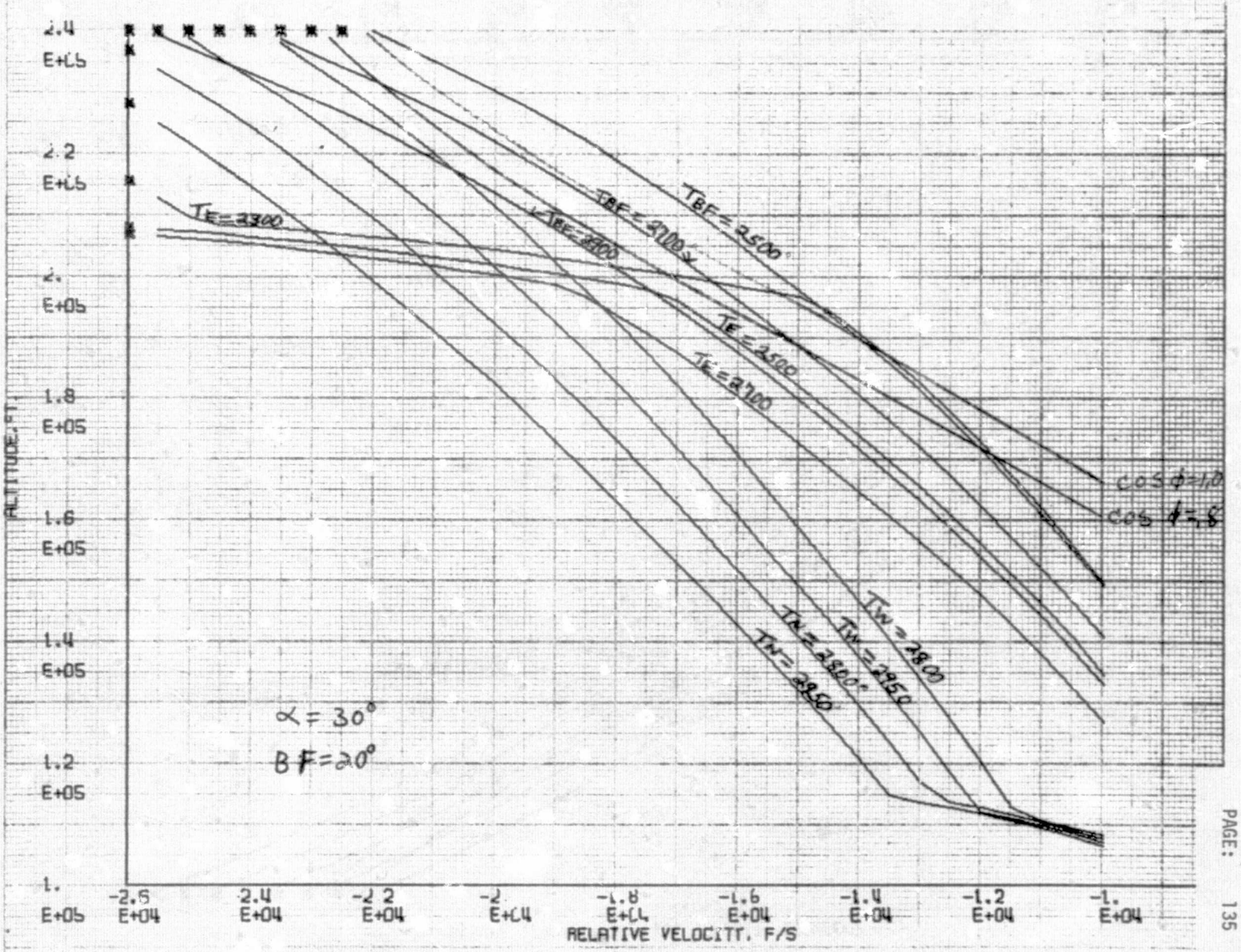

FIGURE 129 ALTITUDE VS. VELOCITY CORRIDOR

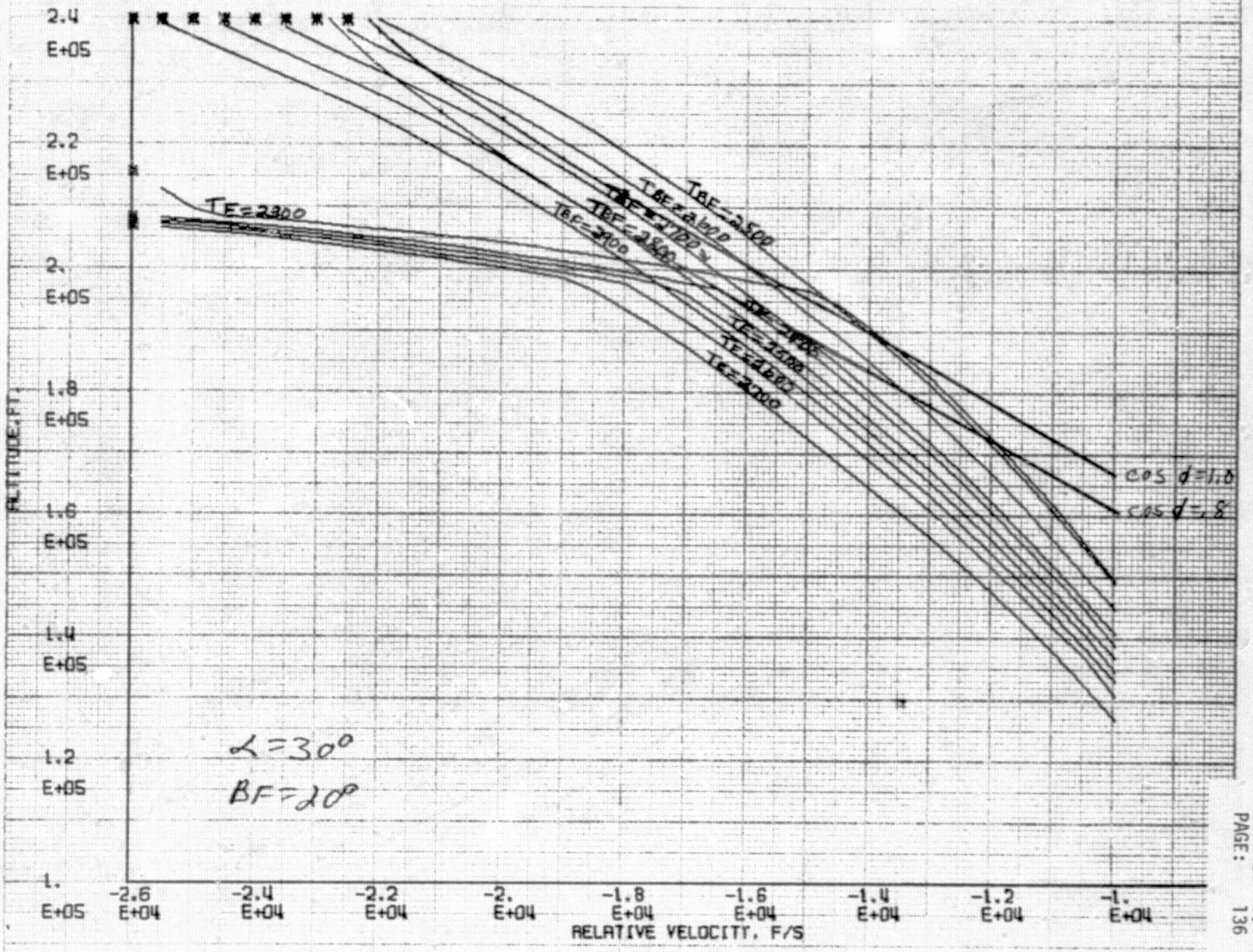

FIGURE 130 ALTITUDE VS. VELOCITY CORRIDOR

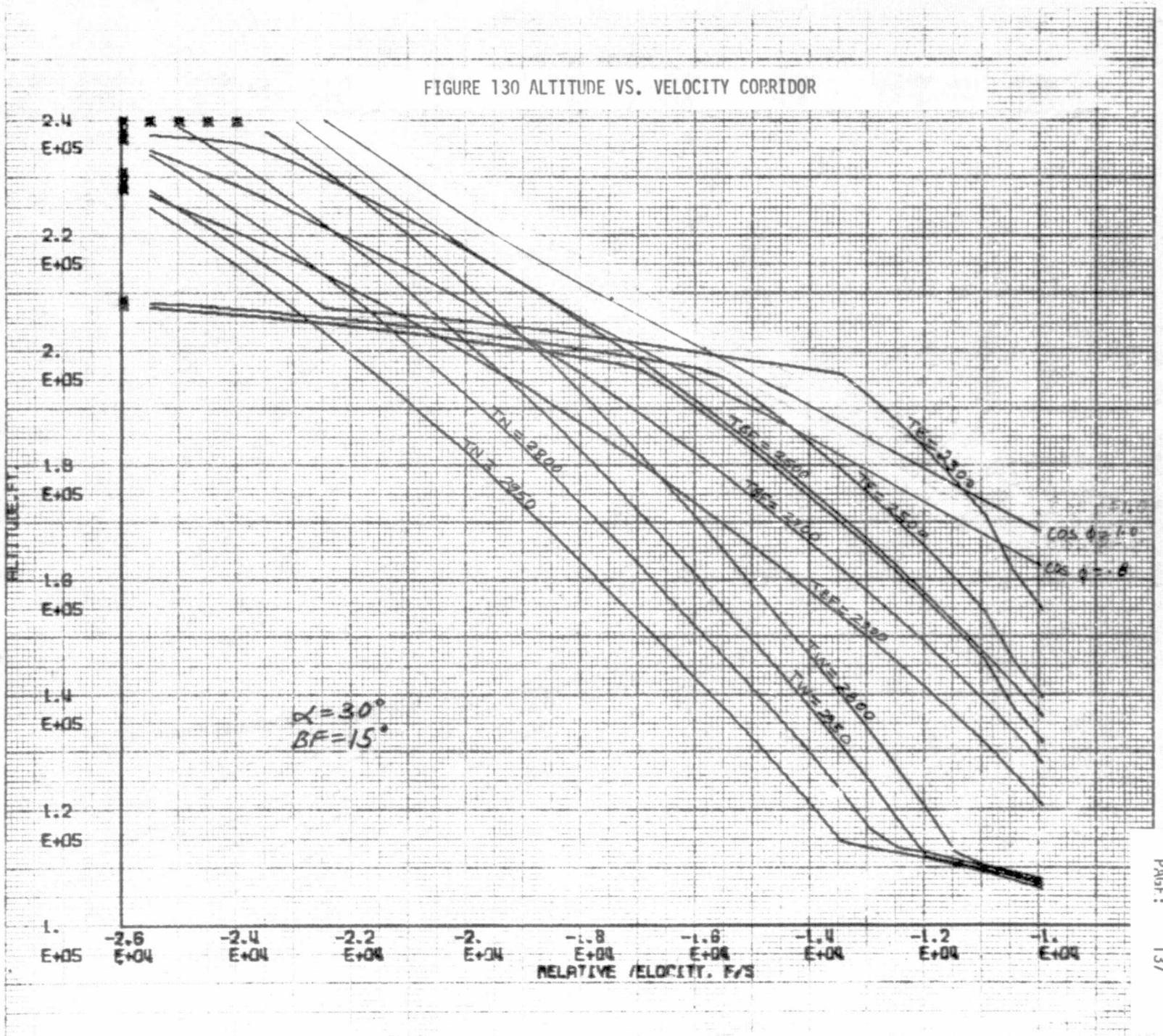

FIGURE 131 ALTITUDE VS. VELOCITY CORRIDOR

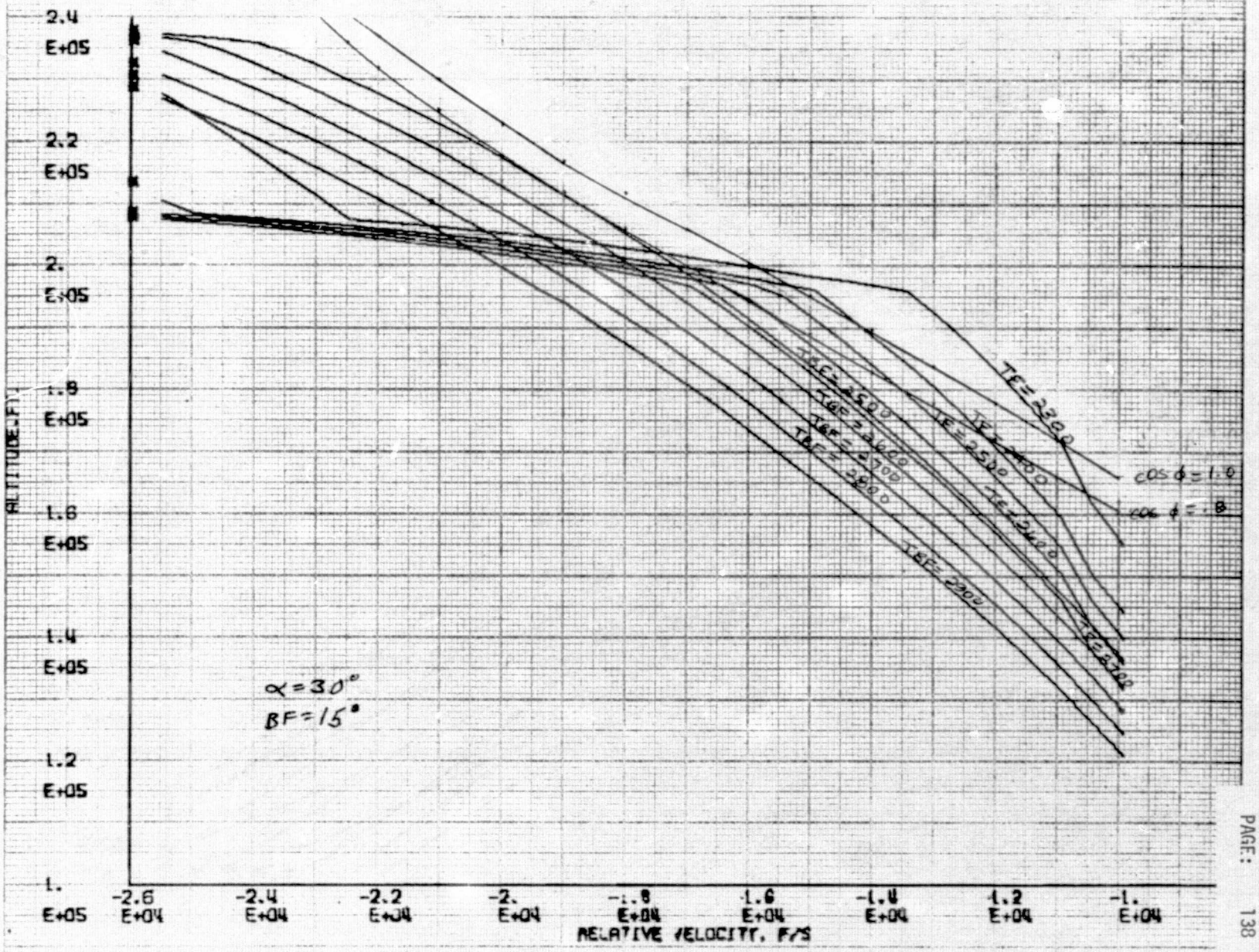

FIGURE 132 ALTITUDE VS. VELOCITY CORRIDOR

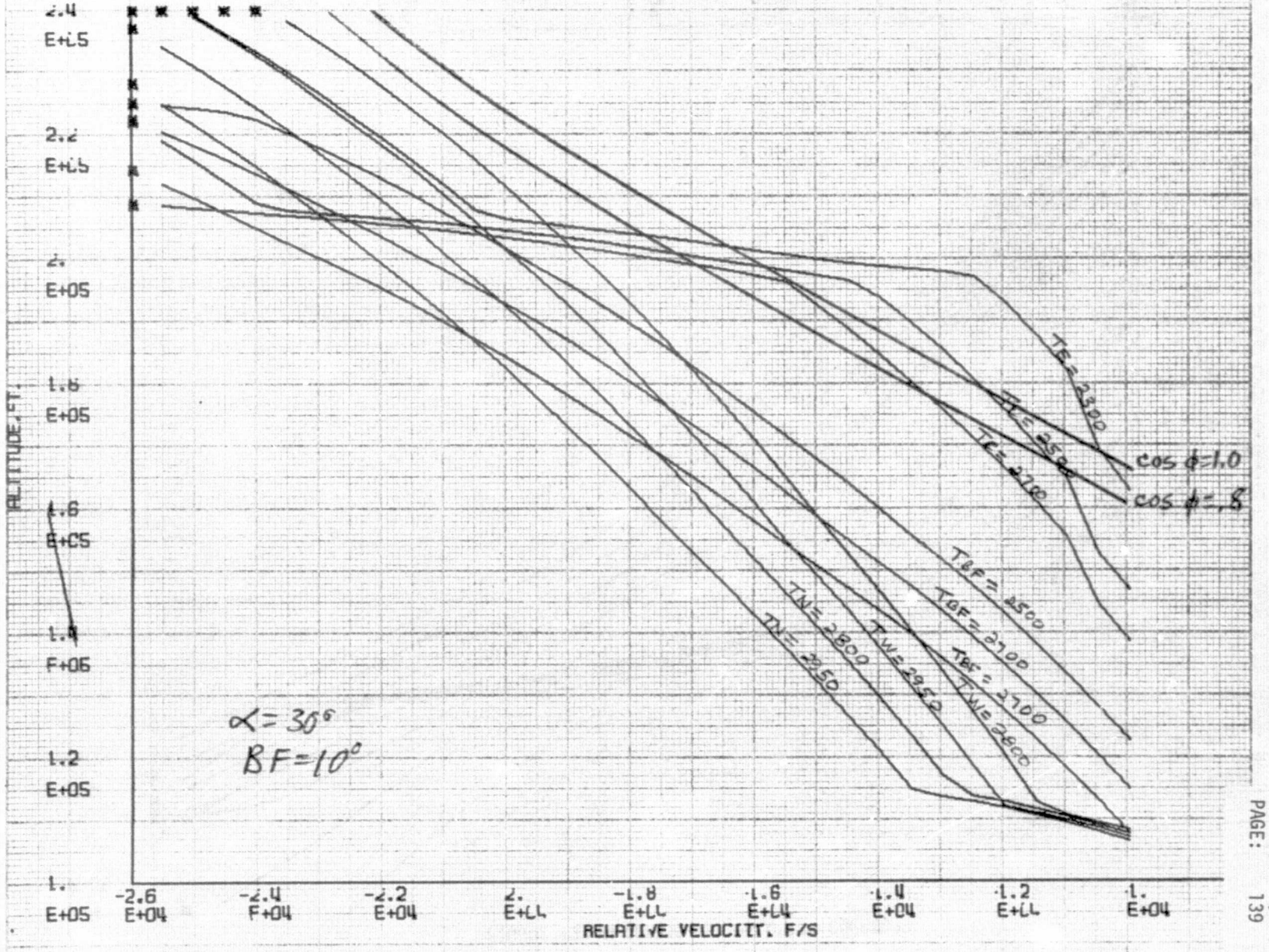

FIGURE 133 ALTITUDE VS. VELOCITY CORRIDOR

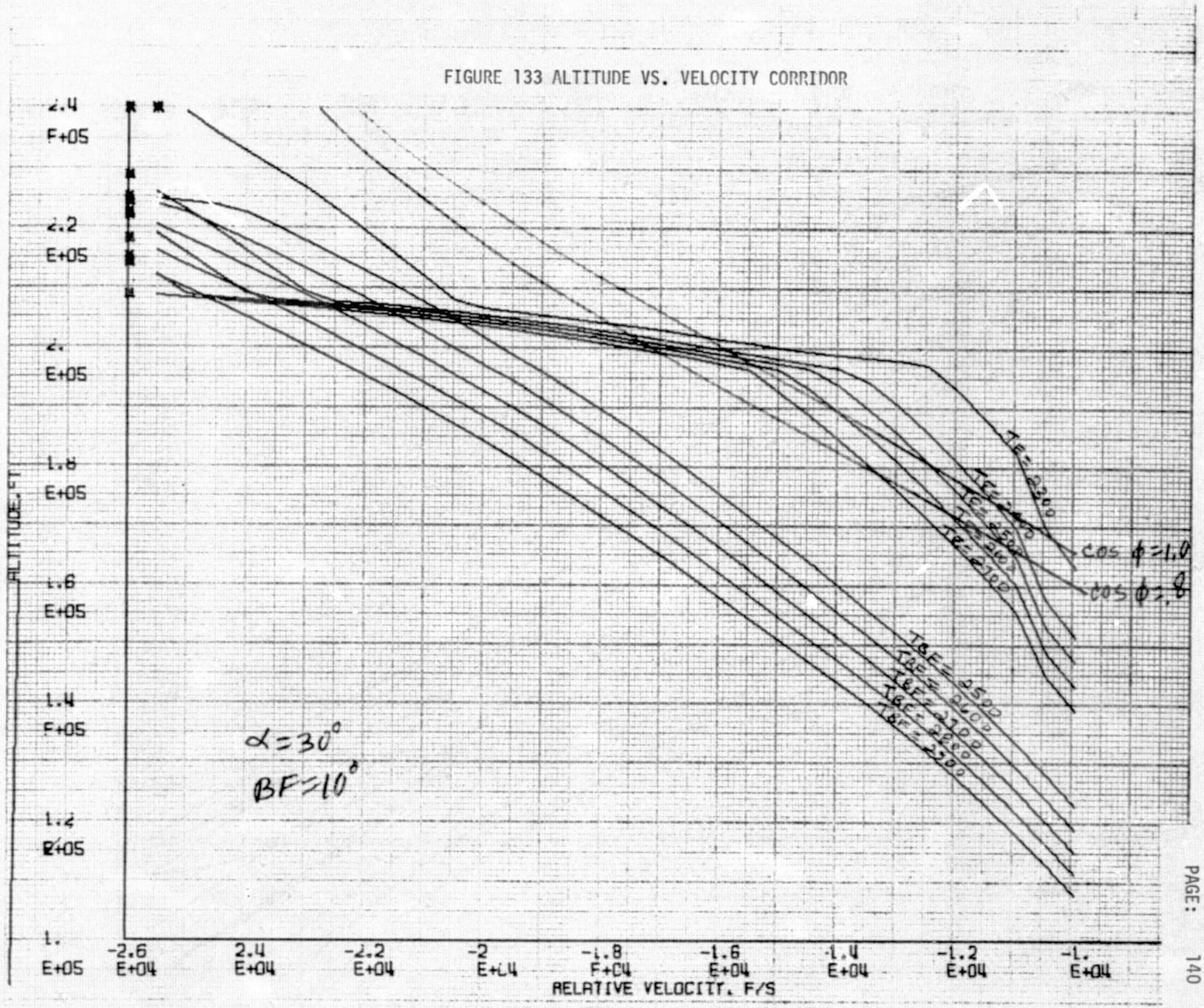

FIGURE 134 ALTITUDE VS. VELOCITY CORRIDOR

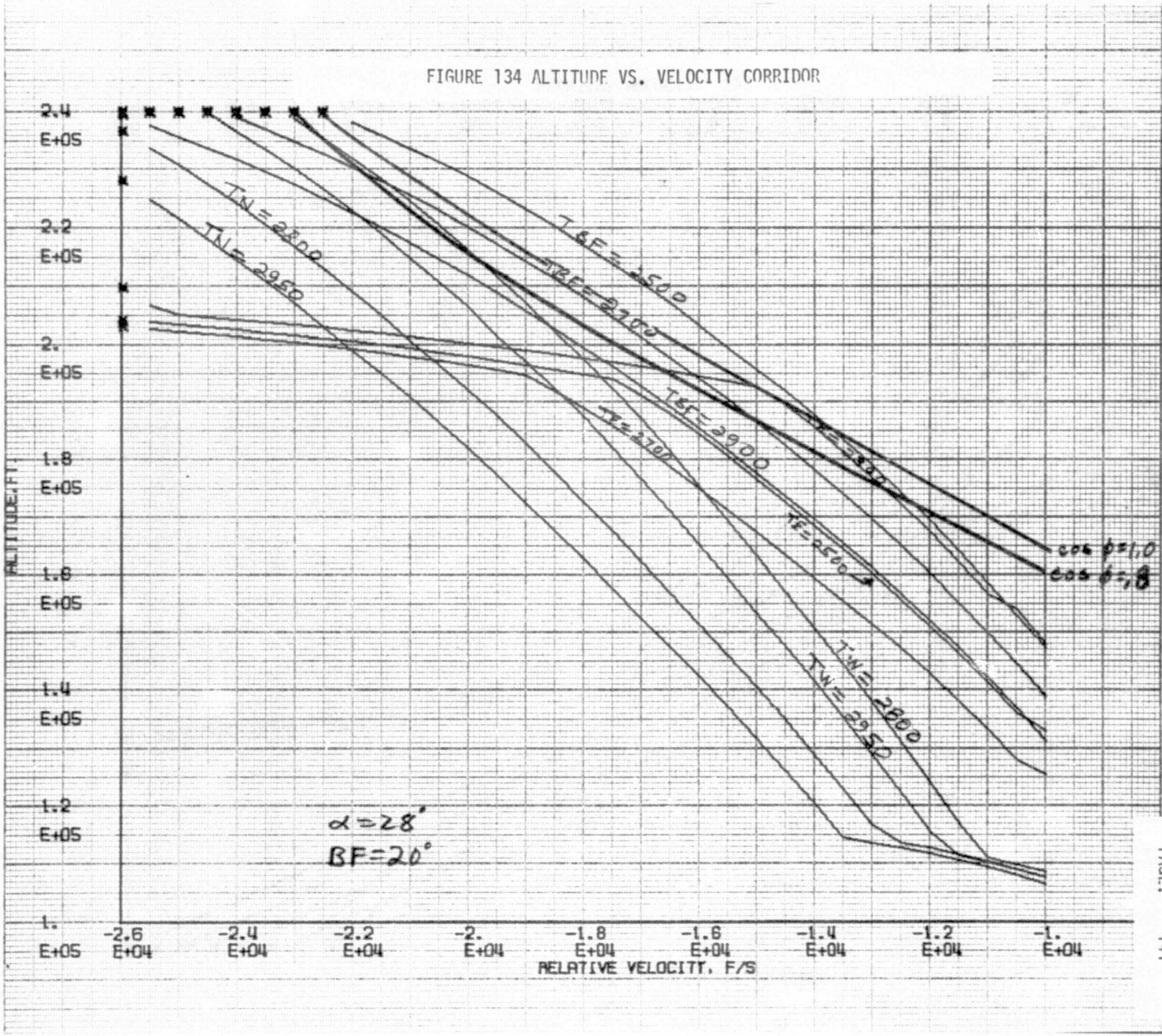

FIGURE 135 ALTITUDE VS. VELOCITY CORRIDOR

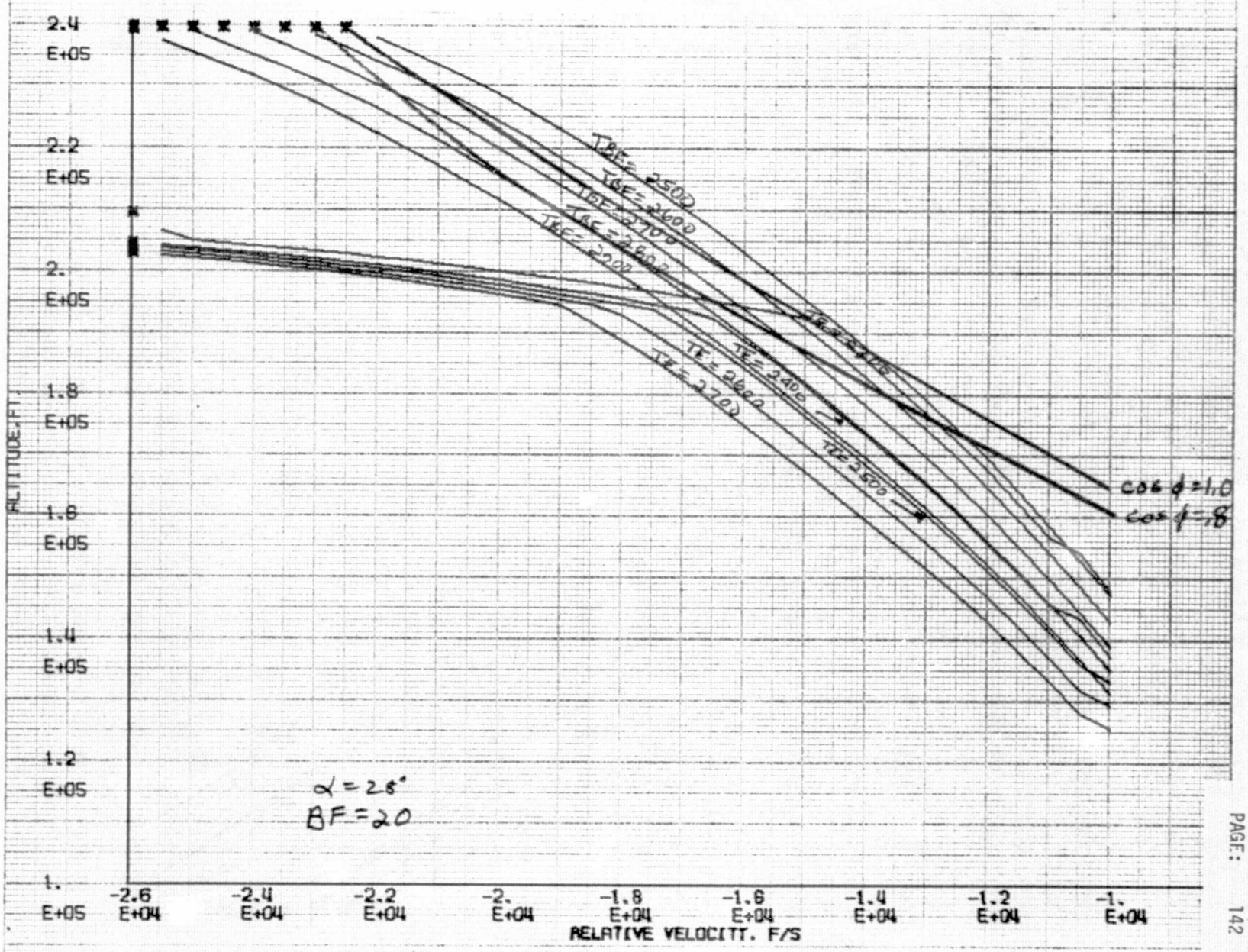

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FIGURE 136 ALTITUDE VS. VELOCITY CORRIDOR

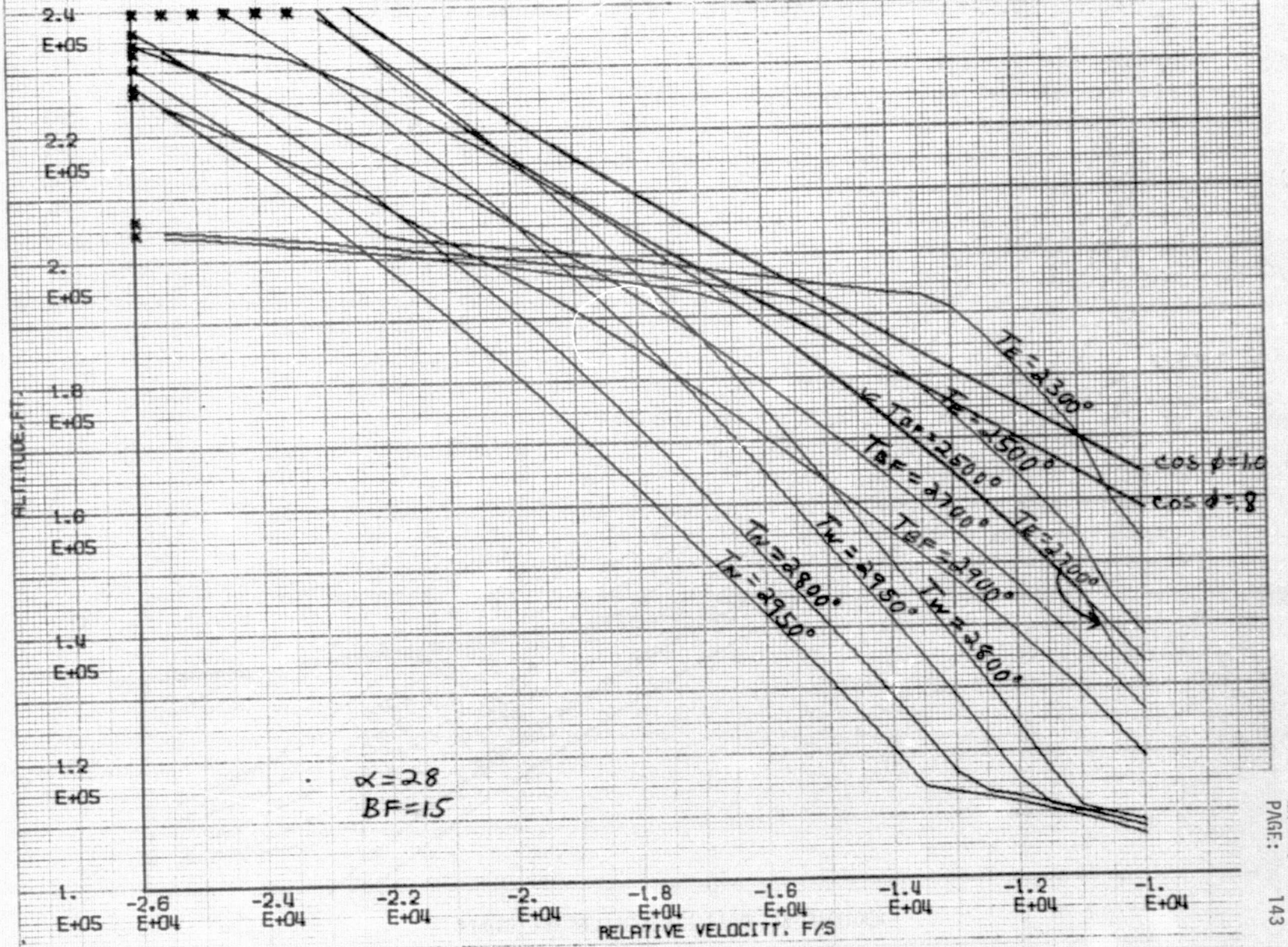

FIGURE 137 ALTITUDE VS. VELOCITY CORRIDOR

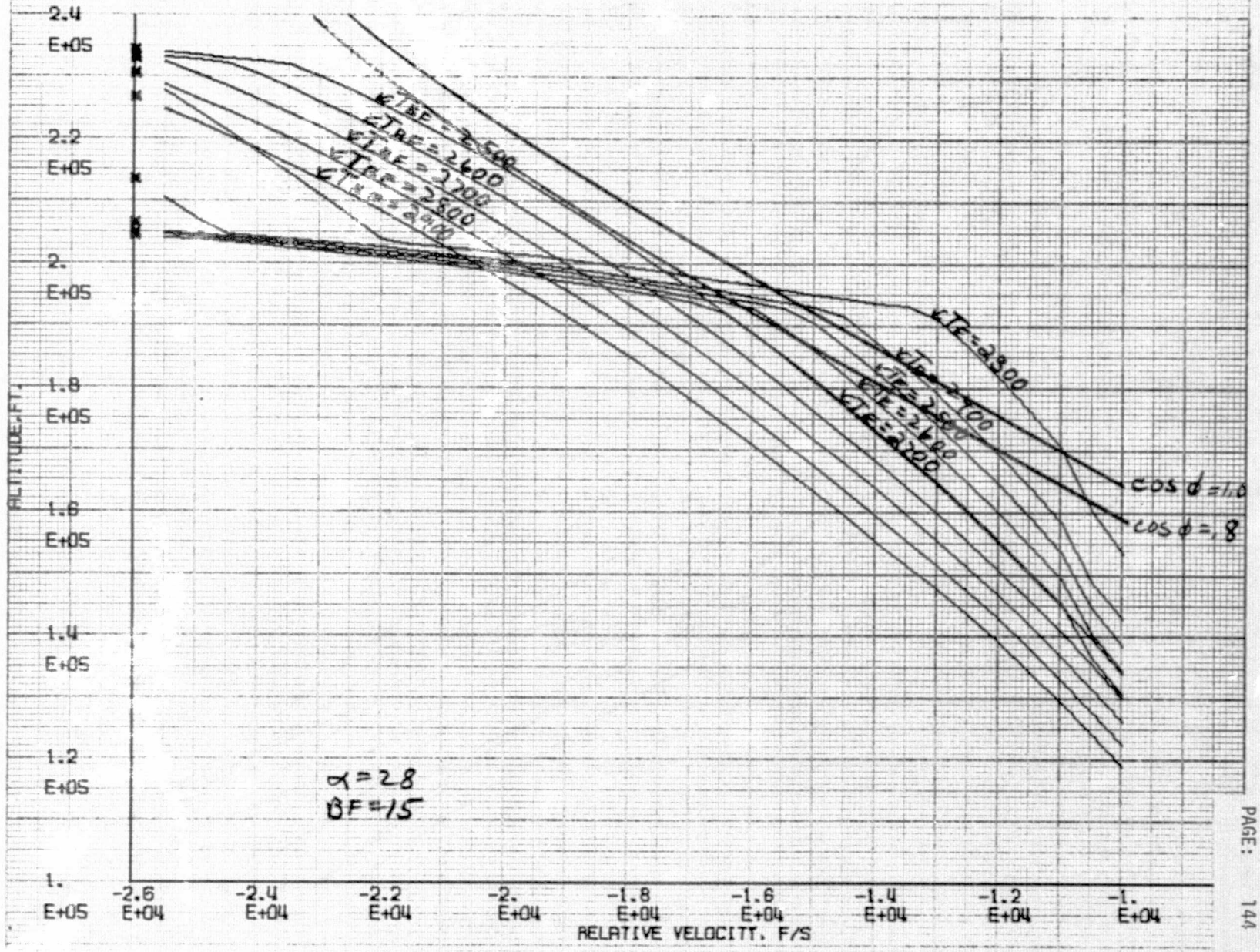

FIGURE 138 ALTITUDE VS. VELOCITY CORRIDOR

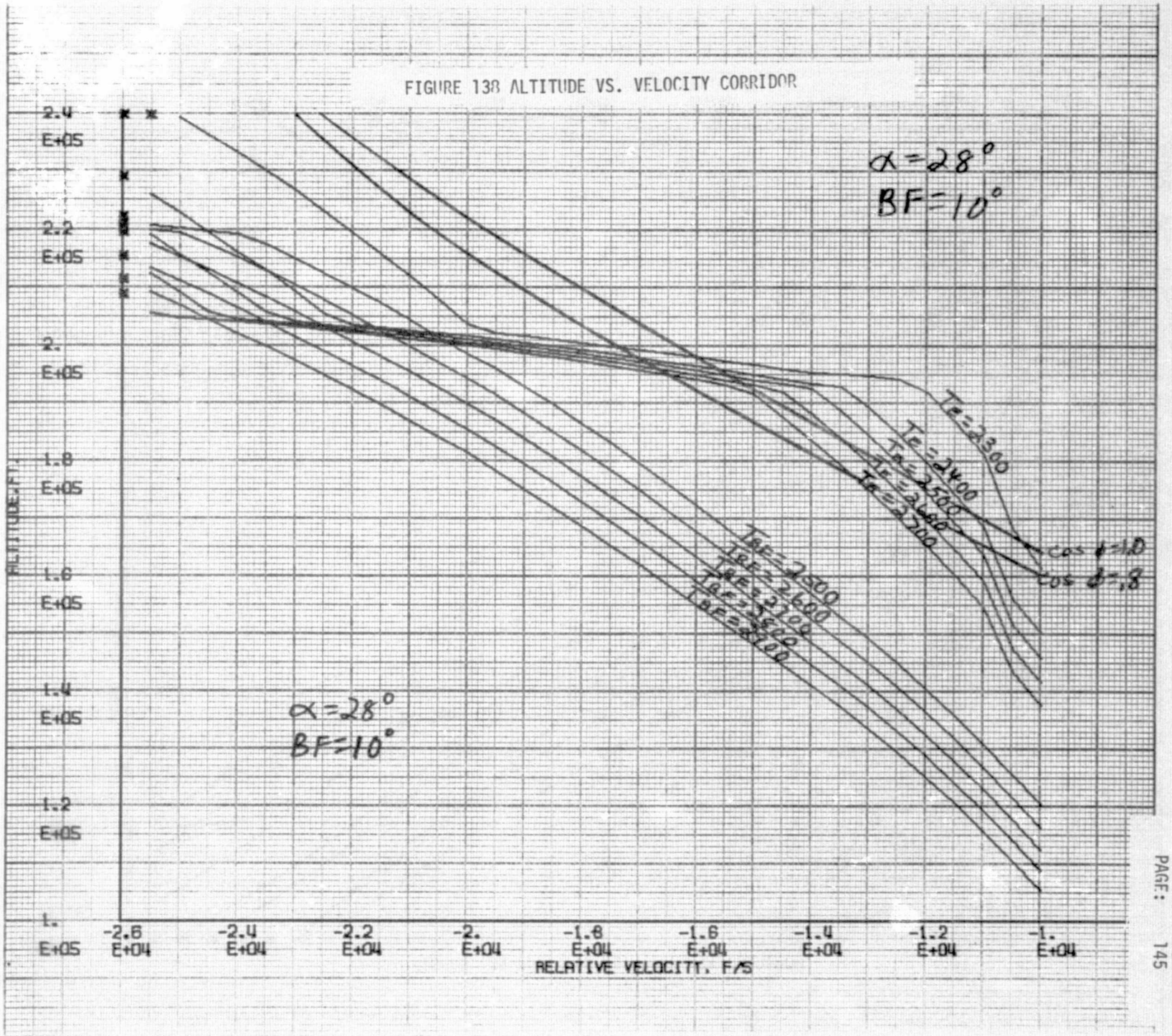

FIGURE 139 ALTITUDE VS. VELOCITY CORRIDOR

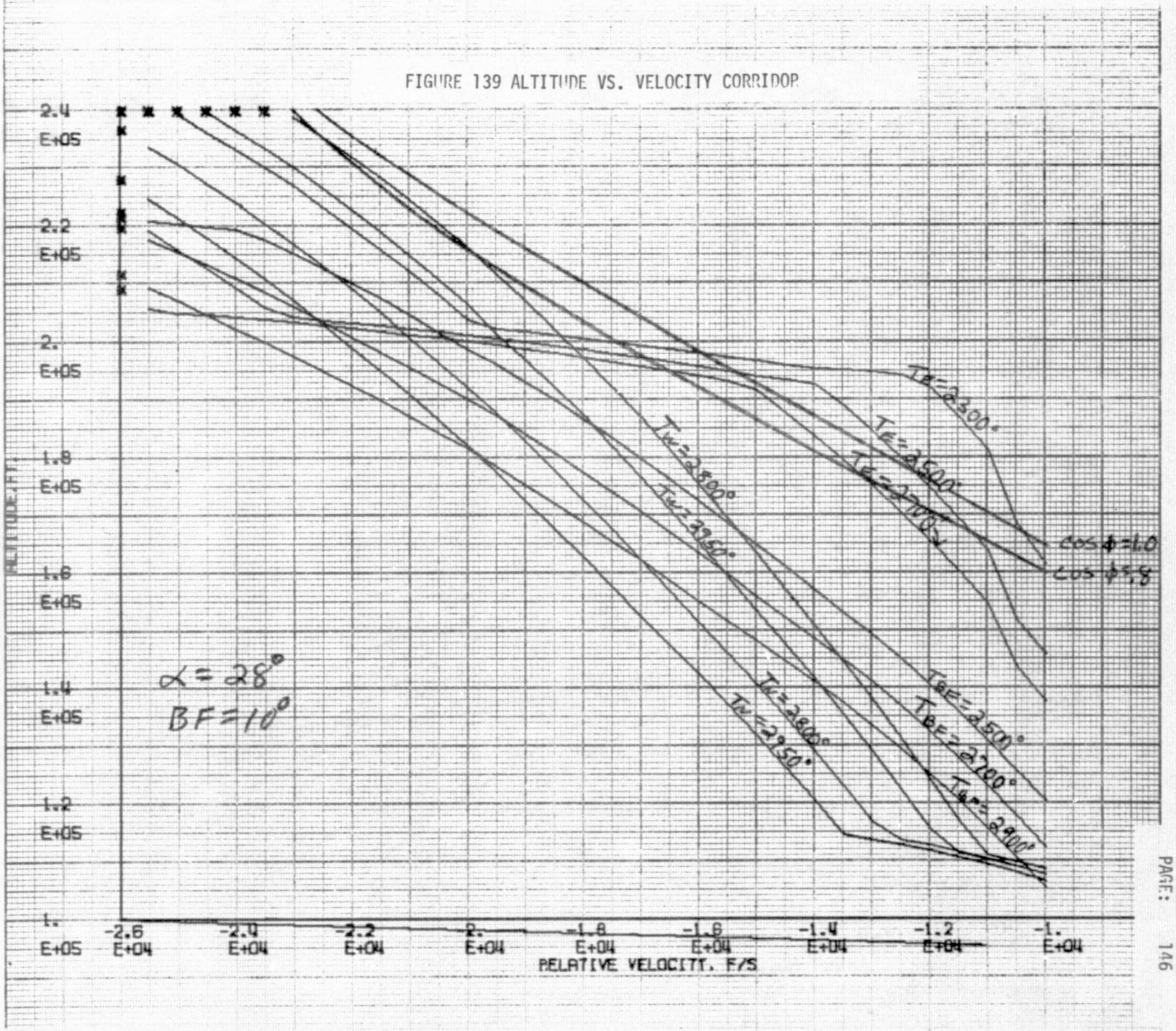

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FIGURE 140 ALTITUDE VS. VELOCITY CORRIDOR

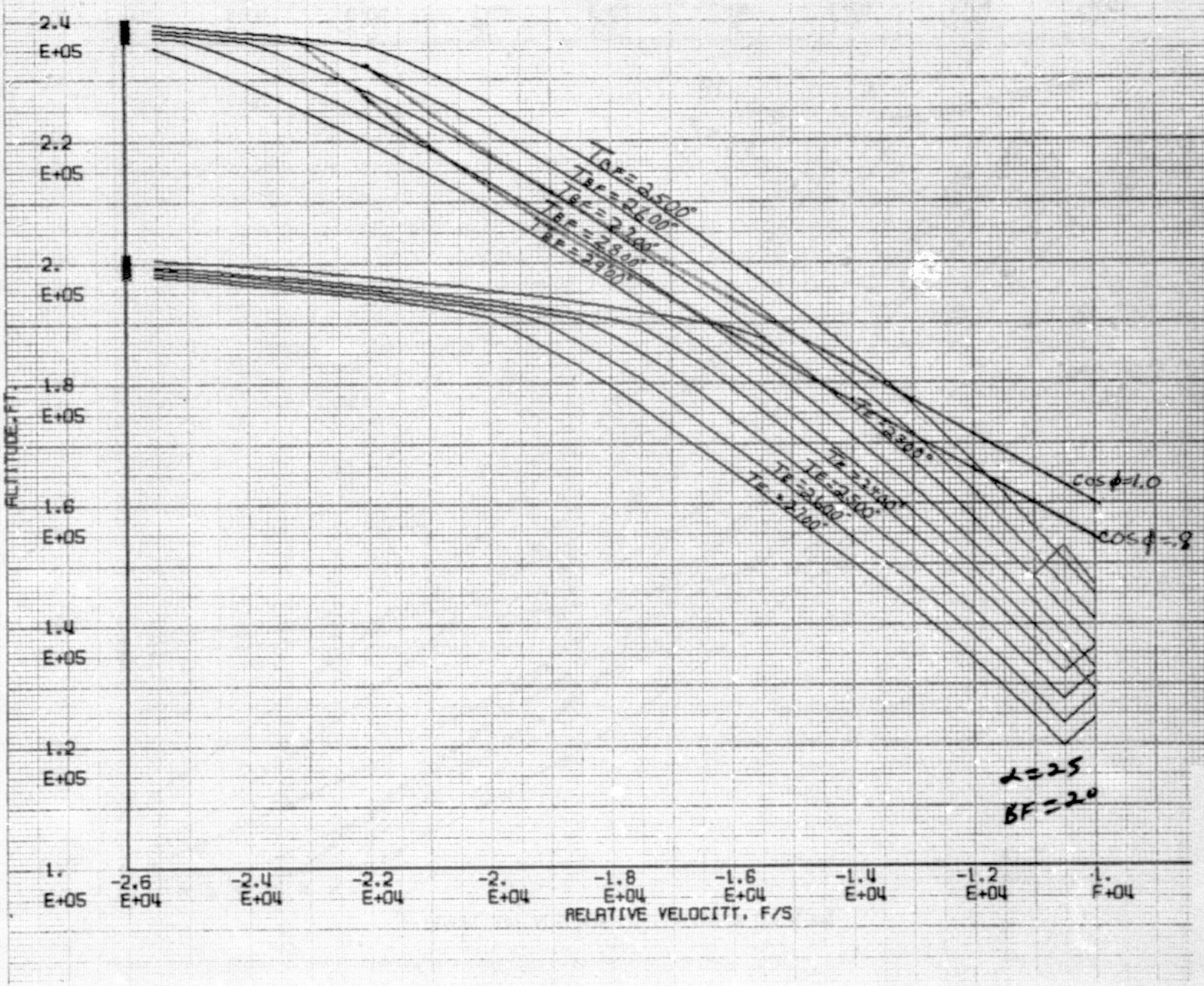

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FIGURE 141 ALTITUDE VS. VELOCITY CORRIDOR

FIGURE 142 ALTITUDE VS. VELOCITY CORRIDOR

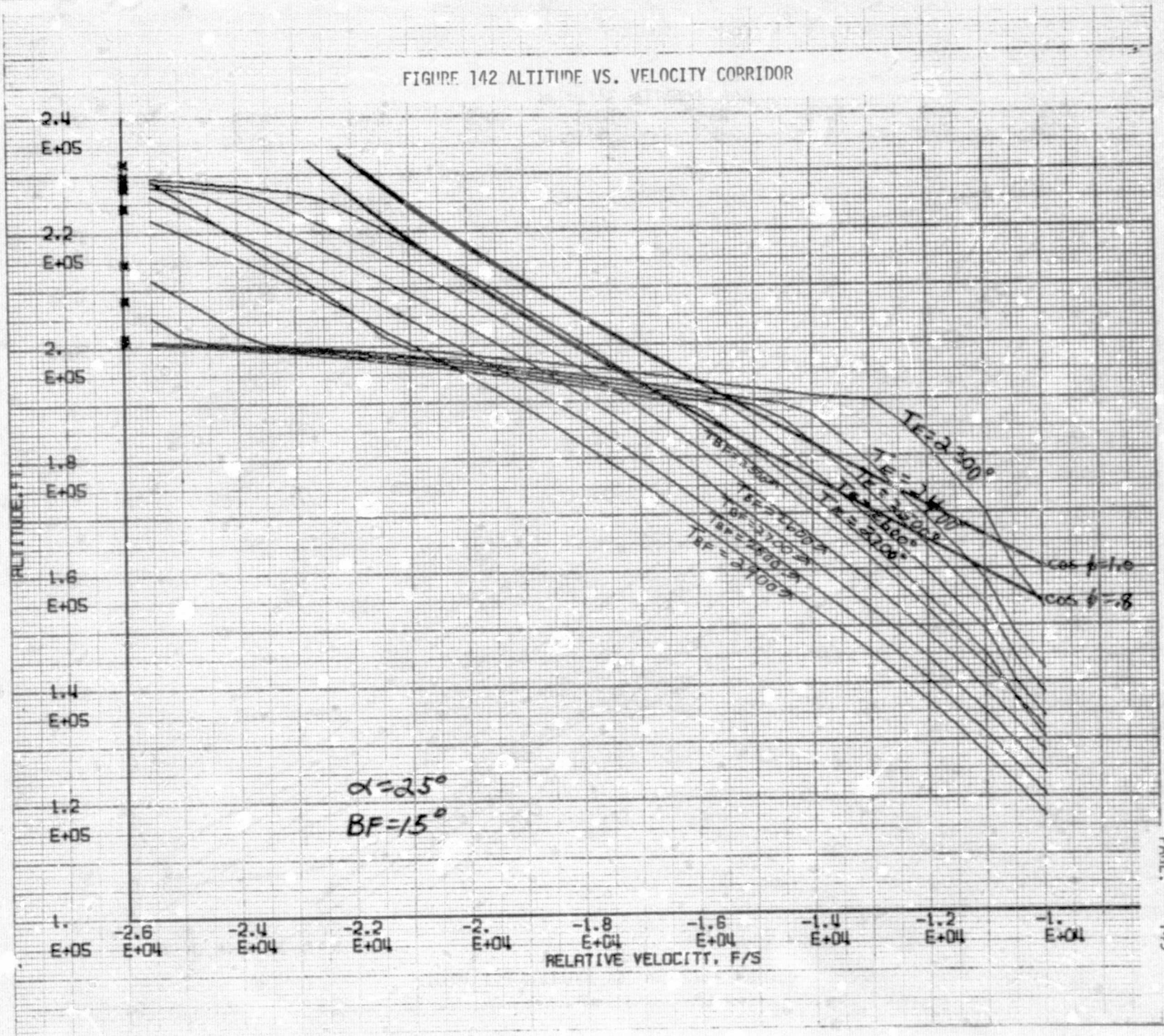

FIGURE 143 ALTITUDE VS. VELOCITY CORRIDOR

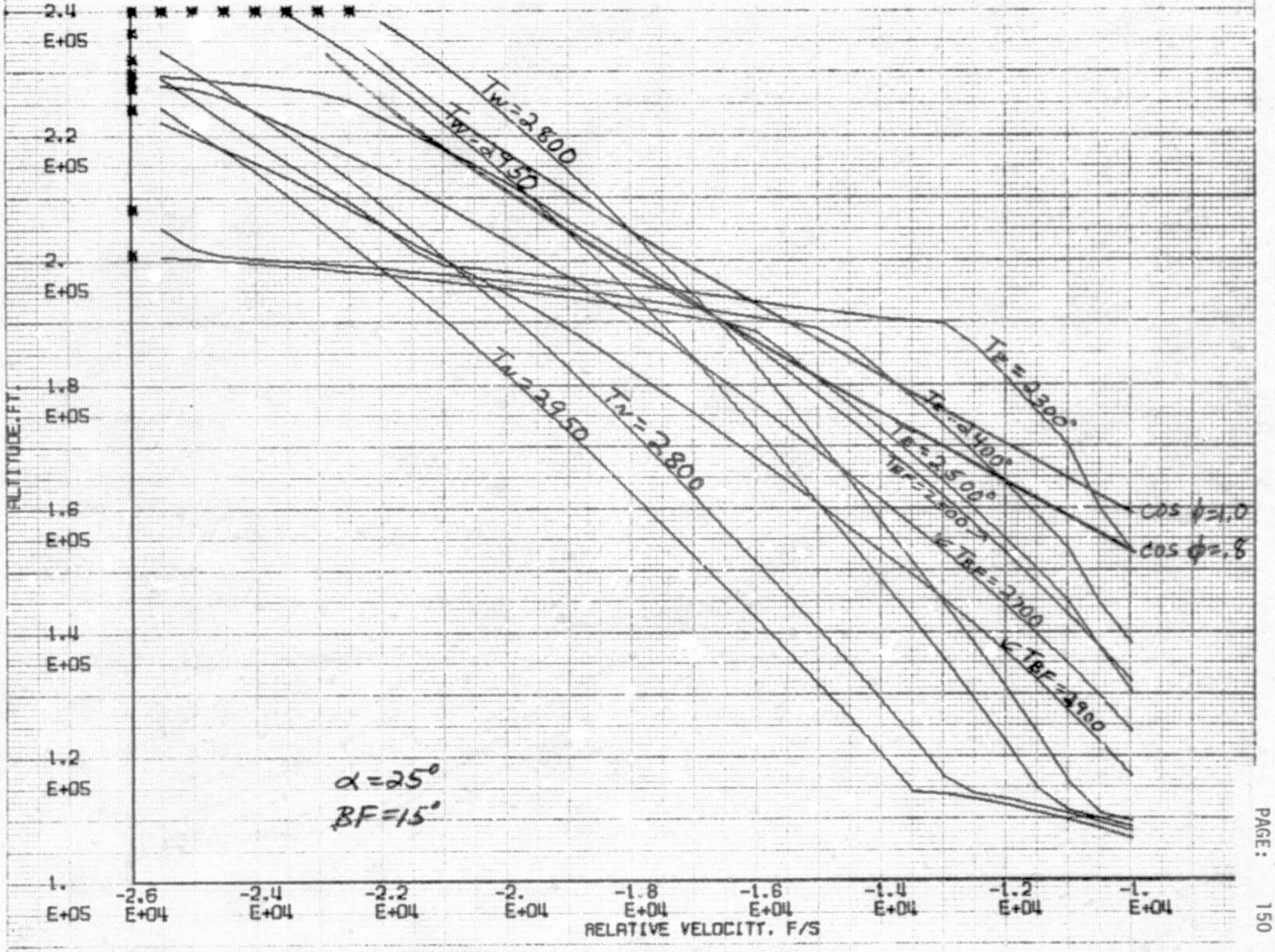

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FIGURE 144 ALTITUDE VS. VELOCITY CORRIDOR

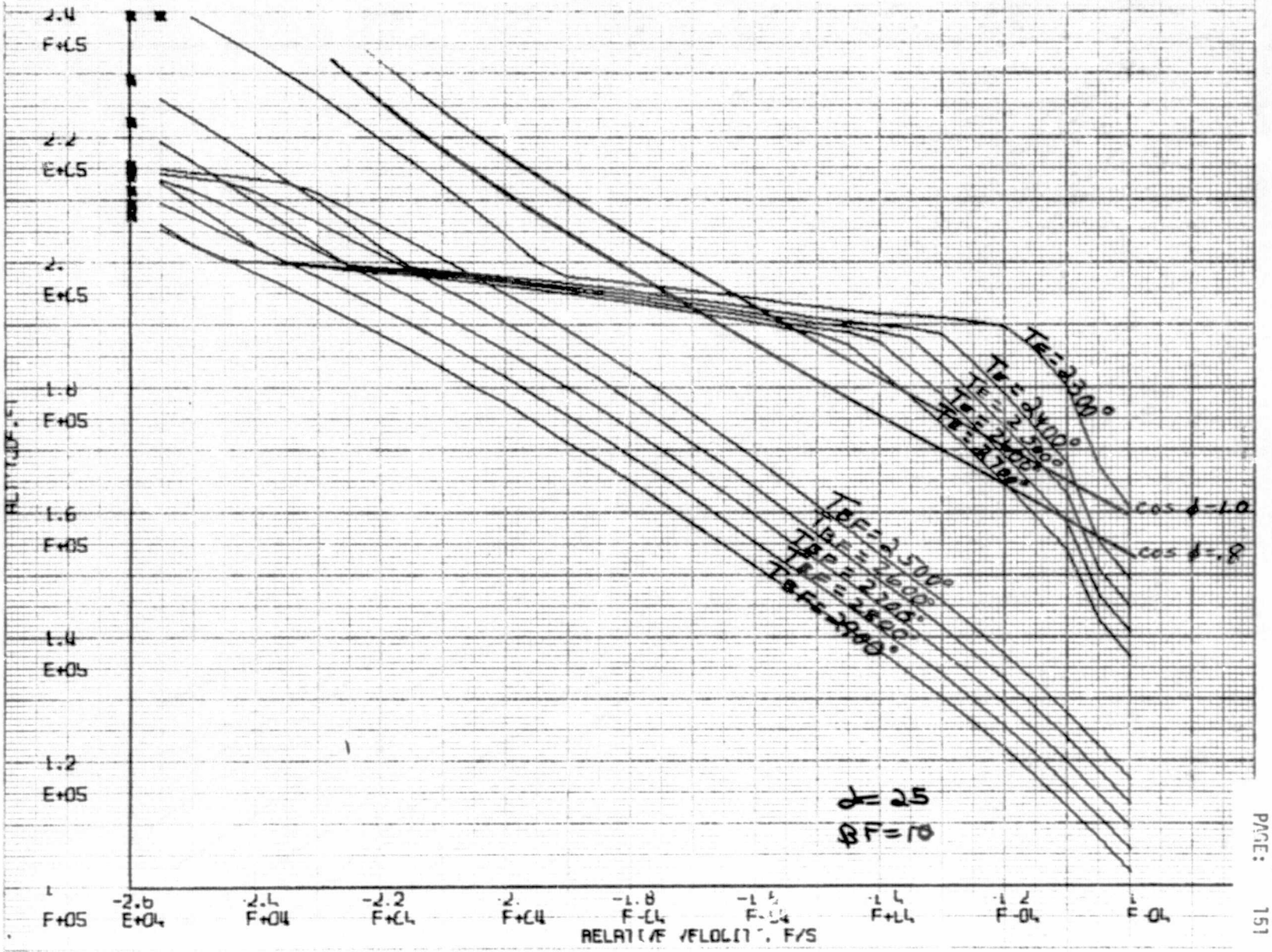

FIGURE 145 ALTITUDE VS. VELOCITY CORRIDOR